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## Comparison of the EarthCraft Multifamily Program to the Objectives of the City of Alexandria Green Building Policy: Final Technical Report

*April 5, 2019*

Viridian considers the EarthCraft Multifamily (ECMF) Gold level of certification to be in substantial alignment with the City of Alexandria's objectives as outlined in Strategy A of the *City of Alexandria Green Building Policy: Final Technical Report*. For some objectives which are not in full alignment, requiring overlay credits of otherwise optional point items can yield the desired results. The below table summarizes how EarthCraft Gold certification outcomes compare to the desired outcomes in Strategy A.

Proposed Metric		EarthCraft Comparison
<b>Energy</b>		
<b>Energy Performance - Site EUI Target</b>	<35 kBtu/sq ft	<p>Gold requires a HERS of 75 or less (lower is better). Of the 1,613 new construction EarthCraft units certified in 2016 and 2017, only 6.8% were over &lt;35 kBtu/sq ft. Of the 929 that scored a 75 or less, only .8% were over 35 kBtu/sq ft, indicating substantial alignment with the City's EUI target.</p> <p>Further, recent research has reported that ECMF units sustain &lt;35 kBtu/sq ft performance over time.<sup>1</sup></p>
<b>Renewable Energy</b>	Designed to have 5% of total site energy provided by onsite renewables	<p>EarthCraft does not require any on-site energy to be provided by renewables at any certification level. IN 1.2 awards optional points for "solar-ready" buildings that are designed and have adequate space to add solar panels that would offset 20% of the electric load. IN 1.3 awards optional points for the installation of solar capacity sufficient to offset 10% of the electric load. Given that both of these exceed the 5% goal, Viridian would not recommend adding either as an overlay credit.</p>
<b>Commissioning</b>	Earn 3 points under LEED v4/v4.1 Enhanced Commissioning	<p>Gold certification provides for commissioning appropriate for residential spaces - blower door testing, duct leakage testing, appropriate HVAC system sizing and equipment selection, refrigerant charge verification, pressure differential testing between bedrooms and the HVAC return, testing and balancing of the HVAC system, static pressure measurement, and ventilation testing. High Rise buildings (6 stories and above) additionally follow a High Rise addendum which requires commissioning of central water heating systems, central heating and cooling system commissioning, and duct testing of central exhaust systems. Alexandria could opt to add the High Rise Addendum as an overlay for multifamily buildings of all sizes.</p>

<sup>1</sup> McCoy, A. Zhao, D., Agee, P., Mo, Y., & F. Paige. (2017). "Sustaining Energy Efficiency: Longitudinal Evidence of Virginia's Low-Income Housing Tax Credit Properties." A Report by the Virginia Center for Housing Research (VCHR) at Virginia Tech for Housing Virginia. August 29, 2017.

<b>Measurement and Verification</b>	Energy metering for the whole building and end uses making up over 10% of the building load	Gold certification does not require M&V due to the difficulties in a residential setting, absent utility companies that are willing to provide whole building aggregated data. IN 1.7 awards optional points for energy monitoring and Alexandria could opt to add this as an overlay credit.
<b>Water</b>		
<b>Indoor Water Use</b>	Reduct of 40% over LEED baseline values	Meeting Gold requirements reduces residential water usage 17% from the LEED v4 for Homes and Midrise baseline. Overlaying WE 1.5 brings this to 33%. Viridiant would propose using the LEED methodology to create a calculator that multifamily project teams can use to demonstrate compliance with the 40% reduction for residential spaces.
<b>Outdoor Water Use</b>	Demonstrate no irrigation is required or 50% reduction in irrigation water use	Gold certification has minimal requirements around landscape water use. Viridiant would support the use of EPA's WaterSense Water Budget Tool, which is also utilized by LEED, to demonstrate compliance regardless of the green building program being pursued.
<b>Stormwater</b>		
<b>Stormwater Management</b>	No requirement beyond the City's current requirement	N/A
<b>Performance Monitoring</b>		
<b>Performance Monitoring</b>	Track data on environmental performance outcomes	IN 1.7 awards optional points to projects that commit to energy monitoring for a sampling of tenant spaces. Additionally, EO 2.3 awards points for pre-occupancy education for tenants on how to best operate their apartments. This education has been shown to result in an average reduction in energy use of 15%. Alexandria could add this as an overlay credit.

## Energy

See below "Energy Code section."

## Commissioning

For many multifamily buildings the bulk of the energy consumption will come from the residential spaces. EarthCraft requires enclosure testing and duct leakage testing<sup>2</sup> for these spaces, mirroring some of the LEED v4 Midrise and ENERGY STAR Multifamily (ESMFHR) requirements. Additionally, for projects 6 stories and higher, EarthCraft requires that a High Rise Addendum be completed, which

<sup>2</sup> Per ANSI 380-2016 Standard for Testing Airtightness of Building Enclosures, Airtightness of Heating and Cooling Air Distribution, Systems, and Airflow of Mechanical, Ventilation Systems.

references the ESMFHR program and requires the commissioning of central water heating systems, central heating and cooling system commissioning, and duct testing of central exhaust systems.

### **Energy Code**

The EarthCraft worksheet does not allow any building to perform below the current energy code. BE 0.1 is a required item on the EarthCraft Multifamily worksheet and states that the project must meet the "IECC adopted by jurisdiction plus applicable state amendments." Residential spaces must then demonstrate energy performance beyond what the energy code requires through achieving a specified HERS index (BE 0.2/BE 0.3). The program exceeds current Virginia energy code by not accepting visual inspection for duct sealing and air sealing, whereas code currently utilizes that as the enforcement mechanism. Points are then available for utilizing above code windows, insulation, and mechanical systems. There are in fact over 90 points available in above-code measures.

Additionally, Integral Group's report suggests adopting a <35 kBTU/sq ft EUI for multifamily residential buildings. In assessing energy models for 947 new construction multifamily units that were EarthCraft certified in 2017 - the most recent readily available data set - the average site EUI was 24.1 kBTU/sq ft. The highest EUI of that data set was 34.6 kBTU/sq ft and the lowest was 17.0, further demonstrating the EarthCraft program's effectiveness as an above-code program..

With that said, Viridiant does support all buildings being held to a maximum EUI to establish a level playing field across green building systems. Given that green building programs are continually in development and have varying metrics by which they assess efficiency, a standardized metric that is easily generated is ideal. It should be specified if this is site or source energy, with source being the preferred metric to equitably handle different fuels that may be used on site. If source EUI is the selected metric, a standardized conversion factor should be provided for converting electricity site use to source in order to prevent gaming.

Furthermore, per EarthCraft IN 1.2, points are awarded for building being solar ready and per IN 1.3 points are awarded for solar offsetting 10% of the projects energy use. These points have been in place since 2015.

### **Measurement & Verification / Metering**

Per Table 8 - Measurement & Verification/Metering, while the report correctly notes that EarthCraft does not require submetering, this is because in almost all cases individual apartments are individually metered, with the exception of specific use cases such as Single Resident Occupancy (SRO) units. Building owners rarely wish to shoulder the burden of tenant utility costs except in those specific use case scenarios.

It is important to note that metering is not the same as monitoring. While Viridiant supports measurement and verification, absent of mechanisms that prompt utility companies to provide aggregated whole building data, this is a non-starter in the multifamily space due to the high barrier to collect utility information from tenants. Viridiant has worked with Virginia Housing Development Authority on various pathways for collecting meter data and establishing minimum sample sets, should the City of Alexandria wish to further discuss these efforts.

### **Water Use Reduction**

Per Table 8 - Water Use Reduction, the report notes that no water performance criteria are called out in the EarthCraft Multifamily program. While a specific percentage may not be called out, this is part of the design of the program. Instead, prescriptive measures are utilized to easily allow projects to achieve the same goals without the need for calculations. Items under WE 1.5 through WE 1.10 are prescriptive measures that lead to that same end.

Additionally, it is worth noting that LEED v4 Homes and Midrise, which is an applicable rating system for all low rise multifamily buildings and all multifamily buildings over 4 stories that have at least 50% residential space, only requires a minimum of 20% reduction (3 points) in indoor water use for any certification level.

By similar comparison, the EarthCraft program, at the Platinum level, requires a 33.4% reduction in indoor water use and the Gold level requires a 17.3% reduction, on average. These figures are based off the indoor water baseline consumption methodology provided in the LEED v4 Homes and Midrise rating system document. Beyond these requirements, points are available for additional water efficiency improvements. Between the requirements and available points, it is inaccurate to state that no water efficiency measures are included in the EarthCraft program.

In order to provide multifamily project teams with a simple way to demonstrate compliance with the 40% reduction target, Viridiant would suggest creating a calculator, based on the LEED v4 Homes and Midrise methodology in Table 1. A format similar to that presented in Table 2 would allow teams to enter their actual fixture flow rates to arrive at an overall reduction percentage.

**Table 1. Indoor water baseline consumption (per person per day)**

Fixture	Baseline flush or flow rate		Estimated fixture usage	Estimated water usage	
Shower (per compartment)	2.5 gpm	9.5 lpm	6.15 minutes	15.4 gallons	58.4 liters
Lavatory, kitchen faucet	2.2 gpm	8.3 lpm	5.0 minutes	11 gallons	41.5 liters
Toilet	1.6 gpf	6 lpf	5.05 flushes	8 gallons	30.3 liters
Clothes washer	9.5 WF	9.5 WF	0.37 cycles @ 3.5 ft <sup>3</sup> (@0.1 m <sup>3</sup> )	15.1 gallons	57.1 liters
Dishwasher	6.5 gpc	24 lpc	0.1 cycles	0.7 gallons	2.4 liters

gpm = gallons per minute  
gpf = gallons per flush  
WF = water factor  
gpc = gallons per cycle  
lpf = liters per flush  
lpm = liters per minute  
lpc = liters per cycle

Source: LEED v4 Homes and Midrise Design and Construction, Updated October 5, 2018, pg 28  
<https://www.usgbc.org/resources/leed-v4-homes-and-multifamily-midrise-current-version>

**Table 2.** EarthCraft Required Water Efficiency per Certification Level

Platinum						
	Daily Usage per Person	Baseline Water Consumption	Total consumption (gal)	EarthCraft Maximum Water Consumption	Total consumption (gal)	Reduction
Shower	6.15 minutes	2.5 gpm	15.375	2 gpm	12.3	20.00%
Lavatory faucets	5 minutes	2.2 gpm	11	1.5 gpm	7.5	31.82%
Toilet	5.05 flushes	1.6 gpf	8.08	1.28 gpf	6.464	20.00%
Washer	0.37 cycles	9.5 WF	15.1	WF	6.8	54.97%
Dishwasher	0.1 cycles	6.5 gpc	0.65	3.5 gpc	0.35	46.15%
Total			50.205		33.414	33.44%

Gold						
	Daily Usage per Person	Baseline Water Consumption	Total consumption (gal)	EarthCraft Maximum Water Consumption	Total consumption (gal)	Reduction
Shower	6.15 minutes	2.5 gpm	15.375	2.5 gpm	15.375	0.00%
Lavatory faucets	5 minutes	2.2 gpm	11	2.2 gpm	11	0.00%
Toilet	5.05 flushes	1.6 gpf	8.08	1.6 gpf	8.08	0.00%
Washer	0.37 cycles	9.5 WF	15.1	WF	6.8	54.97%
Dishwasher	0.1 cycles	6.5 gpc	0.65	3.5 gpc	0.35	46.15%
Total			50.205		41.605	17.13%

Certified						
	Daily Usage per Person	Baseline Water Consumption	Total consumption (gal)	EarthCraft Maximum Water Consumption	Total consumption (gal)	Reduction
Shower	6.15 minutes	2.5 gpm	15.375	2.5 gpm	15.375	0.00%
Lavatory faucets	5 minutes	2.2 gpm	11	2.2 gpm	11	0.00%
Toilet	5.05 flushes	1.6 gpf	8.08	1.6 gpf	8.08	0.00%
Washer	0.37 cycles	9.5 WF	15.1	9.5 WF	15.1	0.00%
Dishwasher	0.1 cycles	6.5 gpc	0.65	3.5 gpc	0.35	46.15%
Total			50.205		49.905	0.60%

## Stormwater

Stormwater, as noted in the report, will be met through the City of Alexandria's requirements. Viridiant has no additional comments.

## Performance Monitoring

EarthCraft does not have requirements for post-occupancy monitoring of certified projects. However, there has been research into the performance of EarthCraft certified units in Virginia and how they performed compared to how they were modeled.<sup>3</sup> The table below summarizes the modeled (Est. EUI) EUI vs the actual performance (Obs. EUI) in the units that were studied.

**Table 3.** EUI Summary

Division	Est. EUI	Obs. EUI	Diff. EUI	N	Std Err	t	p	Upper 95%	Lower 95%
Overall	32.25	25.94	6.31	237	.78	8.11	<0.001**	7.84	-4.78
New	29.75	27.23	2.52	96	1.33	1.89	.031	5.17	-.13
Renovated	33.95	25.05	8.89	141	.88	10.10	<0.001**	10.63	7.15
Senior	34.28	28.42	5.86	89	1.16	5.05	<0.001*	8.16	3.55
Non-Senior	31.03	24.44	6.58	148	1.03	6.36	<0.001**	8.63	4.54

Note: Est = Estimated; Obs = Observed; Diff = Difference; Round-off errors may apply; \*\* = Significant at 99%.

To encourage property owners to more actively manage the energy use of their properties, IN 1.7 - contracting for 12 months of post-construction energy monitoring - and EO 2.3 - provide pre-occupancy briefing for tenants - are encouraged by Viridiant staff when working with project teams. Viridiant has seen an uptick in projects choosing to voluntarily pursue these points.

Given the current difficulty in obtaining tenant level utility data, Viridiant encourages the City to explore partnerships with hardware manufacturers that can provide unit level data monitoring devices, preferably systems that offer instant feedback to tenants on their usage habits.

Viridiant appreciates the City of Alexandria and Integral Group's thoughtful evaluation of programs for consideration of the City of Alexandria's Green Building Policy. We respectfully welcome the opportunity to understand the evaluation process and provide clarification where needed. Please know we applaud the City for this policy revision and aim to support in any way possible.

<sup>3</sup>McCoy, A. Zhao, D., Agee, P., Mo, Y., & F. Paige. (2017). "Sustaining Energy Efficiency: Longitudinal Evidence of Virginia's Low-Income Housing Tax Credit Properties." A Report by the Virginia Center for Housing Research (VCHR) at Virginia Tech for Housing Virginia. August 29, 2017.

**Multifamily New Construction High Rise Addendum**

Appliances		Yes	Must Correct	N/A
<b>Requirement 1</b>	All common area refrigerators, dishwashers, clothes washers, ceiling fans, and vending machines must be ENERGY STAR certified. Prior to purchase, enter the manufacturer and model number into the ENERGY STAR Product Finder to confirm ENERGY STAR certification. Save the results as a PDF and provide to the Technical Advisor.			
Project Team				
Technical Advisor	Field confirm the installation of the documented appliances.			
<b>Central Water Heating</b>				
<b>Requirement 1</b>	Pipes carrying water 105 degrees or hotter must have at least 1" of insulation. Pipes 1.5" or greater in diameter must have at least 1.5" of insulation.			
	Ensure construction documents account for the diameter of the piping plus insulation when passing through any penetrations.			
Project Team	Specify that piping must be inspected by the EarthCraft TA before access is covered up.			
Technical Advisor	Technical Advisor will field confirm the proper installation of piping insulation.			
<b>Requirement 2</b>	Water heating system is commissioned in accordance with manufacturer's start up guidance and controls and settings match the Proposed Design model.			
	Specify commissioning of the water heating system and ensure consistency between the Proposed Design model and the settings and controls in the field.			
Project Team	Witness or collect a letter indicating that commissioning has been performed in accordance with the manufacturer's guidance. The statement should also include an indication of the controls and settings used in the Proposed Design model and confirmation from the installer that these conditions are mirrored in the field.			
TA Steps				
<b>Requirement 2</b>	Verify hot water temperature at all fixtures is no more than 125 degrees			
	When designing the system, consider the water heater set point, branch lengths, and insulation levels to ensure the water temperature is acceptably hot, but no more than 125 degrees.			
Project Team				
Technical Advisor	While performing final testing and using the same sample set, test the hot water temperature at 1 fixture per apartment.			
<b>Building Envelope</b>				
<b>Requirement 1</b>	Common area thermal performance and grade should meet the EarthCraft requirements for the selected certification level. Referencing the thermal performance items required for the selected level of certification, specify the same or better for all non-residential spaces. If higher than typical values are required to meet the energy model for apartment areas, those same or better values must carry through to non-residential areas.			
<b>Project Team</b>				
Technical Advisor	Field verify that there is consistency in the thermal performance of residential and non-residential areas.			
<b>Requirement 2</b>	Window performance should meet the EarthCraft requirements for the selected certification level. When not possible, windows must at minimum be double pane and low-e.			
	Referencing the window performance values required for the selected level of certification, specify the same or better for all non-residential spaces. If code requirements prevent the use of windows that meet the requirements, double pane low-E windows must be specified.			
Project Team				
Technical Advisor	Field verify the performance values of windows in non-residential spaces.			
<b>Requirement 3</b>	Weatherstripping is required at doors between conditioned space and any exterior, unconditioned, or vented to the outside space.			
	Ensure weatherstripping is specified for all doors between conditioned and unconditioned spaces and between conditioned and spaces vented to the outside.			
Project Team				
Technical Advisor	Field verify weatherstripping has been appropriately installed.			
<b>Requirement 4</b>	Garages, including plenums and dropped ceilings, shall not be heated for comfort or to prevent pipes from freezing.			
	Design and locate piping to prevent freezing, either by locating piping in conditioned space or grouping and properly insulating. Heat tracing may be used, but it must be activated based on pipe wall temperature and be set no higher than 40 degrees. The energy usage must be accounted for in the Proposed Design model.			
Project Team				
Technical Advisor	Visually confirm that garages, including plenums and dropped ceilings, are not heated. If heat tracing is used, confirm the thermostat temperature does not exceed 40 degrees.			
<b>Central Heating and Systems Serving Common Areas</b>				
<b>Requirement 1</b>	Pipes carrying water 105 degrees or hotter must have at least 1" of insulation. Pipes 1.5" or greater in diameter must have at least 1.5" of insulation. Ductwork must be sealed with mastic and have a minimum of R-6 insulation in unconditioned spaces.			
	Ensure construction documents account for the diameter of the piping plus insulation when passing through any penetrations.			
Project Team	Specify that piping must be inspected by the EarthCraft TA before access is covered up.			
Technical Advisor	Field confirm the proper installation of piping insulation or sealing and insulation of duct work.			
<b>Requirement 2</b>	Heating system is commissioned in accordance with manufacturer's start up guidance and controls and settings match the Proposed Design model.			
	Specify commissioning of the water heating system and ensure consistency between the Proposed Design model and the settings and controls in the field.			
Project Team	Witness or collect a letter indicating that commissioning has been performed in accordance with the manufacturer's guidance. The statement should also include an indication of the controls and settings used in the Proposed Design model and confirmation from the installer that these conditions are mirrored in the field.			
Technical Advisor				
<b>Central Cooling and Systems Serving Common Areas</b>				

<b>Requirement 1</b>	Cooling system is commissioned in accordance with manufacturer's start up guidance and controls and settings match the Proposed Design model.			
Project Team	Specify commissioning of the water heating system and ensure consistency between the Proposed Design model and the settings and controls in the field.			
Technical Advisor	Witness or collect a letter indicating that comissioning has been performed in accordance with the manufacturer's guidance. The statement should also include an indication of the controls and settings used in the Proposed Design model and confirmation from the installer that these conditions are mirrored in the field.			
<b>Requirement 2</b>	Ductwork must have a minimum of R-6 insulation in unconditioned space and be sealed with mastic. Pipes carrying water 60 degrees or less must have a minimum of .5" insulation. Pipes 1.5" or greater in diameter must have at least 1" of insulation.			
Project Team	Ensure construction documents account for the diameter of the piping plus insulation when passing through any penetrations.			
Technical Advisor	Specify that piping must be inspected by the EarthCraft TA before access is covered up. Technical Advisor will field confirm the proper installation of piping and duct insulation.			
<b>Common Area, Exterior, Garage, and Other Non-Residential Lighting</b>				
<b>Requirement 1</b>	Total specified lighting power for the combined non-apartment spaces must not exceed ASHRAE 90.1-2010 allowances for those combined spaces by more than 20%.			
Project Team	Provide a schedule with manufacturer, model, total wattage, bulb type, control, location, and quantity of each lighting fixture.			
Technical Advisor	Provide calculations showing the proposed lighting vs the ASHRAE 90.1-2010 allowance. Field verify the proposed lighting or equivalent has been installed.			
<b>Requirement 2</b>	At least 80% of installed light fixtures must be ENERGY STAR certified or have ENERGY STAR certified lamps installed.			
Project Team	Provide submittal of the manufacturer's cut sheet for each type of light fixture installed. Ensure any ENERGY STAR labels remain attached to the fixture.			
Technical Advisor	Field verify the proposed lighting or equivalent has been installed.			
<b>Requirement 3</b>	All exit sign lighting shall be LED or photoluminescent. LEDs shall not exceed 5W per face.			
Project Team	Provide submittal of the manufacturer's cut sheet.			
Technical Advisor	Field verify the proposed lighting or equivalent has been installed.			
<b>Requirement 4</b>	All non-apartment spaces, except those intended for 24 hour operation or where automatic shutoff would endanger the safety of occupants, must have occupancy sensors or automatic bi-level lighting controls.			
Project Team	Include type and quantity of controls and associated fixtures in lighting schedule.			
Technical Advisor	Field verify proposed controls have been installed with the associated fixtures. Verify occupancy sensors, timers, photocells, daylighting controls, and occupancy dimmers are set correctly and functioning.			
<b>Motors</b>				
<b>Requirement 1</b>	All 3-phase pump motors 1 horsepower or larger shall meet or exceed efficiency standards for NEMA Premium.			
Project Team	Provide cut sheets for all applicable motors and documentation that the NEMA Premium standards have been met. Allow access to the Technical Advisor to verify the installation.			
Technical Advisor	Field verify the installed motor matches the cut sheet.			
<b>Air Sealing and Compartmentalization</b>				
<b>Requirement 1</b>	Continuity of air, water, and thermal barriers must be provided around the entire building enclosure, including between conditioned spaces and unconditioned spaces within the building, mechanical rooms vented with unconditioned air, chases open to unconditioned spaces, elevator shafts and stairwells, and garages.			
Project Team	Ensure drawing, details, and sections show continuity of these items. Specify that materials used in these systems are compatible with each other.			
<b>Common Area Ventilation and Duct Leakage</b>				
<b>Requirement 1</b>	All central and common area ventilation, exhaust, and heating/cooling duct work is sealed with mastic.			
Project Team	Specify mastic or other UL-181 compliant material shall be applied to all transverse joints, takeoffs, and transitional junctions of the ducts. Specify all connections between walls/floors/ceilings and duct work must be sealed.			
<b>Requirement 2</b>	Any central exhaust systems that serve at least 1 apartment must be tested prior to sheetrock. The maximum allowable leakage is 5 CFM per register per shaft plus 5 CFM per floor per shaft.			
Project Team	Allow access to inspect and test ducts prior to enclosure.			
Technical Advisor	Test the duct work at either 50 or 100 pascals with the duct blaster connected to the roof curb and the pressure probe approximately 5' downstream and its face perpendicular to the air flow. Once sheetrock is installed, visually verify boots have been sealed to it.			
<b>Requirement 3</b>	Verify that the efficiency of ventilation and exhaust fans matches specified equipment. Confirm associated controls match specified equipment.			
Project Team	Provide cut sheets for each type of ventilation and exhaust fan and the associated controls.			
Technical Advisor	Field verify the installed equipment matches the cuts sheets.			
<b>Water Efficiency</b>				
<b>Requirement 1</b>	All lavatory faucets, showerheads, and tank type toilets must be WaterSense labeled.			
Project Team	Specify WaterSense labeled lavatory faucets, showerheads, and tank type toilets. Provide cut sheets.			
Technical Advisor	Confirm installed fixtures match the provided cut sheets.			

# COMPARISON OF GREEN HOME ENERGY PERFORMANCE BETWEEN SIMULATION AND OBSERVATION: A CASE OF VIRGINIA, UNITED STATES

Andrew P. McCoy, Ph.D.<sup>1</sup>, Dong Zhao, Ph.D.<sup>2</sup>, Teni Ladipo, Ph.D.<sup>3</sup>, Philip Agee<sup>4</sup>, and Yunjeong Mo<sup>5</sup>

## ABSTRACT

The United States has a long-term goal to reduce 50% of energy usage in buildings based on 2010 consumption levels. Home energy efficiency is often measured by laboratory experiments and computational simulation. Thus, there is little to no quantifiable evidence showing the extent of energy efficiency homes can achieve within the larger context of green building standards. The objective of this research is to identify actual home energy performance as an effect of green building technologies by comparing energy use from real-world observations and energy modeling. Results indicate a significant reduction of energy consumption at 43.7% per unit or 43.4% per square foot (i.e., 0.093 m<sup>2</sup>) and substantial financial savings at \$628.4 per unit or \$0.80 per square foot (i.e., \$8.6 per m<sup>2</sup>) annually. Savings account for 2% of median annual household income or 46% of energy cost expenditures for an American home. Results also identify the construction type as a significant factor, yet building technology is not the only factor influencing a home's energy efficiency. The findings contribute to the body of knowledge in three aspects: (1) simulated energy usage is higher than actual energy usage; (2) energy modeling via simulation tools is particularly accurate for new construction; and (3) energy modeling, especially for existing buildings, is not accurate due to largely varying occupant behaviors.

## KEYWORDS

building construction, sustainability, housing, energy efficiency, environmental systems, energy simulation

## 1. INTRODUCTION

According to the U.S. Department of Energy (DOE 2014), homes and commercial buildings constitute 39% of the nation's energy usage, more than manufacturing or transportation industries. Long-term goals for the U.S. are to reach 50% energy savings in building energy use

1. Professor, Myers-Lawson School of Construction, Virginia Tech, VA 24061

2. Assistant professor, School of Planning, Design & Construction, Michigan State University, MI 48824. E-mail: dzhao@msu.edu (Corresponding author)

3. Project Associate, Wiss, Janney, Elstner Associates, Inc, VA 22031

4. PhD student, Myers-Lawson School of Construction, Virginia Tech, VA 24061

5. PhD student, School of Planning, Design & Construction, Michigan State University, MI 48824

based on 2010 levels of energy usage. To secure these savings, research, development, prescriptive systems and next-generation building technologies are being utilized to advance building systems and energy performance. Based on the U.S. Census Bureau (2016), 23.5% of home improvement projects have completed at least one energy-efficiency project, representing over 9% of all owner-occupied units in the nation, with 32,000 such projects constructed within the last four years.

Energy efficiency is beneficial for homeowners and builder-developers. Homeowners report utility savings and interest in efficiency, despite the upfront costs. Builder-developers also report benefits from energy efficient design, construction operation, and maintenance despite initial costs (Yudelsohn 2008; Zhao et al. 2017). Since 2006, the architectural, engineering, and construction (AEC) firms have increasingly put employees through certification training and conducted certified projects at increasingly higher levels, showing internal commitment to sustainable principles. While designing and building to a certified standard is now the price of admission for the industry at large, a differentiating point needs to focus on results.

The nation's housing stock is moving towards green building while the understanding of actual performance from such green building technology has not caught up with the trend. In the literature, energy efficiency is often described by laboratory experiments or computational simulation (Clarke et al. 2002; Menassa et al. 2013; Nguyen et al. 2014), which appears to be theoretical. There is little to no observed evidence showing the extent of what energy efficiency homes can achieve within the context of a green building standard. In the absence of such evidence, subjective evaluations of the green building technologies and their contributions to energy use reduction remain likely. Therefore, the objective of this research is to identify home energy performance as an effect of green building technologies through comparing observations and computational energy modeling of energy use. The comparison aims to find discrepancies in home energy efficiency between real-world building use and designated expectations. In reaching this goal, the work is expected to answer the following three questions:

1. Is the actual green home energy performance different from computational simulation?
2. Does the green home energy performance vary by construction type and occupant type?
3. What are the financial savings resulting from green homes and what are their implications for homeowners, builders, and the housing industry?

The next sections of this work are organized as follows. Section 2 will introduce the background of the U.S. residential industry and its green building standards. Section 3 will describe data collection and analysis methods to compare observed home energy efficiency with the estimation from design (energy modeling). Section 4 will describe results of the comparison that indicates the actual home energy performance and variations to the design. Section 5, based on the identified energy performance, will discuss the impacts of green building standards on homeowner expenditures, housing affordability, building codes, and construction costs. Section 6 will outline conclusions drawn from this empirical study.

## **2. BACKGROUND**

### **2.1 Definition of Home Energy Performance**

Green building is gaining acceptance as a sign of excellence in the United States, limiting the options in the market for firms that cannot bring these skills to a building project (McCoy et al. 2012). Energy prices, regulation, and health or safety concerns are all factors that increase

the need for the adoption of energy efficient and ‘green’ practices in the building construction field (Simcock et al. 2014). An inclusive and comprehensive definition of green buildings helps understand and assess building performance.

Many studies have attempted to define high-performance housing; however, there is no one standard definition. Most definitions emphasize energy efficiency, sustainability, and environmentally friendly products (Adomatis 2012). Lewis et al. (2010) defined a green building as one “that is designed, constructed and operated to minimize environmental impacts and maximize resource efficiency, while also balancing cultural and community sensitivity.” In the same article, sustainability is defined as development that meets the needs of the present, without compromising the ability of future generations to meet their own needs. Though some may argue that these definitions are more theoretical than practical, within industry these definitions have often been applied while considering the triple bottom lines: balancing environmental, economic, and social goals (Hodges 2005). The Dictionary of Real Estate Appraisal (Appraisal Institute 2010) describes green design and construction as “the practice of developing new structures and renovating existing structures using equipment, materials, and techniques that help achieve long-term balance between extraction and renewal and between environmental inputs and outputs, causing no overall net environmental burden or deficit.” The U.S. Energy Independence and Security Act (Sissine 2007) defined a high-performance building as “a building that integrates and optimizes on a lifecycle basis all major high performance attributes, including energy [and water] conservation, environment, safety, security, durability, accessibility, cost-benefit, productivity, sustainability, functionality, and operational considerations.” Additionally, many professionals are now defining their practices as green without utilizing the prescriptive systems that avow these methods (Tucker et al. 2012). In summary, the authors prefer human-centered energy efficiency to define a building’s energy performance, which represents the human–building interactions in a sociotechnical system, including occupant, technology, and building systems.

## ***2.2 Measurement of Home Energy Performance***

It is critical to evaluate the designed building’s performance after construction in terms of energy consumption, utilities, operations and maintenance, and occupant health (Fowler et al. 2005). While designers and builders might define high-performance buildings as ones that use innovative appliances and technologies, Turner and Vaughan (2012) warns that a high-performance house is not necessarily a “high tech” one (sensors and programmable appliances and equipment are likely to be common features in the near future). The current literature considers consensus-based metrics to evaluate features in a green building project related to specific key indicators (i.e. energy efficiency, indoor air quality, site use, and etc.). Five specific leading determinants directly affect energy consumption in buildings (Bros-Williamson et al. 2016; Emery and Kippenhan 2006; Santin et al. 2009; Yu et al. 2011): building features (e.g., construction type), building technology (e.g., cooling/heating systems), occupant features (e.g., number of occupants), occupant behavior (e.g., activities conducted), and climate (e.g., outdoor air temperature).

In the U.S., three rating systems are Energy Star, the Leadership in Energy and Environmental Design (LEED) for Homes, and the National Association of Homebuilder’s (NAHB’s) National Green Building Standards (NGBS). A high-performance residential building might be a certified home but every certified home is not necessarily a high performing one. According to Korkmaz et al. (2010), green, sustainable, and high-performance homes are designed and constructed to maximize the energy efficiency of the envelope, mechanical

and lighting systems to provide superior quality in the indoor environment for enhancing occupant well-being. In general, homes that can be described as high-performance fall into categories: 1) safer and healthier; 2) more energy and resource efficient; 3) more durable; and 4) more comfortable. Such buildings are being widely adopted for their potential to reduce energy costs and improve the health and productivity of occupants. To achieve the set goals for a high-performance residential project within realistic financial and time constraints, though, superior planning, design, and construction processes are needed. Turner and Vaughan (2012) pointed out high-performance houses as requiring planning, creative and innovative design, and efficient implementation. A high-performance house may also need to fit into federal and state goals, local law or others' needs (the home buyer, architect, builder or manufacturer).

Nationally and regionally, independent building contractors and tradespeople are the stakeholders primarily responsible for implementing green buildings in the residential built environment (McCoy, O'Brien, et al., 2012). These stakeholders are also primarily responsible for either veto or endorsement of innovative products, processes, and systems in residential construction (Koebel 2008; McCoy et al. 2008; Slaughter 1998). According to Ng (2009), "Green building means improving the way that homes and homebuilding sites use energy, water, and materials to reduce impacts on human health and the environment." While the intent and concept is straightforward, early adopters among independent building contractors and tradesmen have recognized a need for communicating specific benchmarks of green building, similar to the "organic" label used for produce. This type of product certification helps to manage expectations, provide measurable deliverables, and establish a metric that can be tied to economic value. Similarly, high-performance construction, such as green building, establishes expectations, measurable deliverables, and metrics for professionals through green building certification programs and training. Both are integral to green building and lend confidence to the risks in implementing a new and relatively unknown system. The industry has moved quickly to address these risks, as almost 50 local and regional green building labeling programs have emerged, many of which have resulted in pieces of national-level programs.

### ***2.3 Environmental and Economic Implications***

A variety of influences impact either directly or indirectly household energy use. According to the U.S. Department of Energy (DOE, 2011), the most significant contributors to residential energy consumption include the domains of space heating, space cooling, water heating, lighting, electronics, and appliances. Durak (2011) reviewed previous research, building science fundamentals, energy assessment tools, and commonly accepted business practices in order to identify a comprehensive list of energy consumption influence parameters that drive the demand and expenditure of energy consumption domains in the residential setting. Interrelationships between the energy consumption domains and identified household energy consumption influence parameters were investigated to aid in the future development of more accurate energy models. A summary of the relationship analysis undertaken for the study can be exemplified with the total square footage parameter. Total square footage impacts heating and cooling requirements as well as the lighting energy consumed by a household. The bigger the square footage, the more energy required to meet these needs. Total square footage of a house does not only impact energy consumption items but can additionally affect other influence parameters such as footprint area, the number of rooms, and volume. Changes to the total square footage can, in turn, alter the affected influence parameters and thus impact the energy consumption items they influence.

Home energy efficiency has environmental and economic implications to broader society (Gillingham et al. 2009). Energy efficient housing is critical when considering overall energy demand and consumption, as the impacts are complex and far reaching. The fiscal health of a household can be closely tied to the cost burden of energy expenditures. The energy cost incurred from household operation can be significant; such cost has the potential to create financial hardship for a household. While this is true for all households, irrespective of income level, it holds especially true in the case of low-income households. High-performance homes are not necessarily easy to embrace, either. One of the primary barriers in the green market is the owner's perception of higher initial costs associated with these homes due to added personnel hours and use of innovative materials and technologies (Konchar and Sanvido 1998). Processes and technologies used to deliver green building projects need to remedy this problem (Beheiry et al. 2006; Lapinski et al. 2006). Expenditures resulting from energy consumption largely contribute to a homeowner's costs and becomes a growing consideration during home construction and maintenance. Lee et al. (1995) noted that the cost of energy bills is influenced so strongly by decisions made during design and construction that it necessitates taking a life-cycle perspective when evaluating housing. Lee further stated, "Investment in energy efficiency measures may increase purchase price yet decrease future energy bills." The DOE estimates that the typical household spends approximately 8–14% of their income on energy expenditures. Of this, a third typically is consumed by energy demands for heating and cooling needs (DOE, 2011). This indicates that for the typical American household, heating and cooling costs consume approximately 3–5% of their gross annual income. This percentage is considerable when counting the rising housing cost burden. Today, more than one-in-three American homeowners and one-in-two renters are considered to be cost burdened (Zhao et al. 2015). It is estimated that 12 million renters and homeowners dedicate more than half of their annual incomes to housing expenses. Utility expenses may further affect a homeowner's financial ability to afford to live in a home.

In summary, high-performance homes have significant impacts on the nation's environment and economy, yet a well-established definition and measurement of a high-performance home has not been achieved from the literature. Thus, there is a critical need to explore the residential buildings' realistic energy performance using empirical data analysis. This research fills such a gap by analyzing home energy performance using real-world energy usage and building conditions.

### **3. METHODS**

The presented research was designed to examine home energy performance by comparing observed (actual) and estimated (modeled) energy use. The comparison aims to identify actual home energy efficiency as a result of adopting green building standards and technology. The observed energy consumption data were retrieved from utility bills across a whole year. The estimated energy consumption data were computed using building energy analysis software (REM/Rate software) across individual residential units. The researchers employed comparative statistical analysis and regression analysis to examine differences and to explore contributing factors.

#### **3.1 Data**

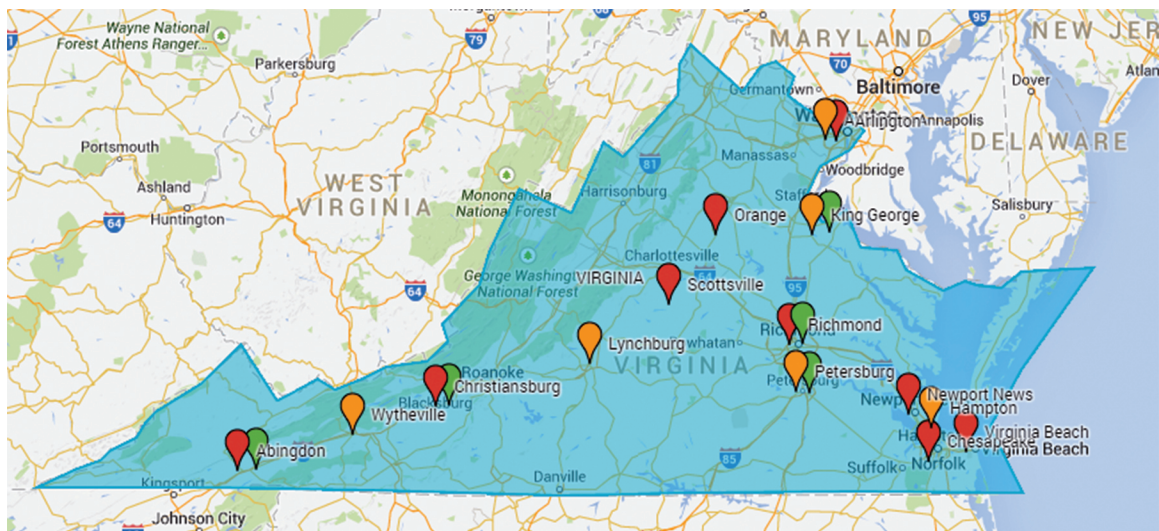
The initial sample in this study contains 312 individual residential units from 16 residential developments across the geography of the State of Virginia (see Figure 1). Based on the Virginia

Housing Development Authority's green building requirements in its Qualified Allocation Plan (QAP), Virginia has recently become ranked highest among states in the southeast U.S. for producing green affordable buildings. Virginia is also one of the top states in terms of attractiveness to tax credit investors as a result of its healthy economy, steady growth, and strong rental housing market. The combination of all of these factors makes residential buildings in Virginia an ideal and available target for this research.

The sample units included varying combinations of construction type (new and renovated) and occupant type (senior occupants and non-senior occupants). New construction project units were located in the counties or cities of Arlington, Hampton, King George, Lynchburg, Petersburg, and Wytheville. Renovated project units were located in the counties or cities of Abingdon, Arlington, Chesapeake, Christiansburg, Orange, Richmond, Scottsville and Virginia Beach. In the U.S., senior occupants are defined as residents of age 55 and above (HUD, 2013). The shortest rental lease included in the data was 12 months. As context, it is noteworthy that this work is the first effort to capture this amount of information for such a large geography and within one common standard.

The sample selection was based on the building's geographical location, application of Energy-Efficiency (EE) retrofit technologies, and sustainable construction practices. The selected units are all built or renovated after 2009, which ensures the availability of state-of-art energy-efficiency technologies for all the units during construction. Another criterion for selection is that the units were required to meet the green building standard of Home Energy Rating System (HERS). HERS presents the energy rating of a home's energy efficiency. The HERS Index is a nationally recognized scoring system for measuring a home's energy performance. Based on the results of field testing and energy modeling, an energy rated home receives a HERS Index score. A score relates the home to the average new standard home construction (commonly termed code-built) in America. A score of 100 is equal to new standard home construction. Lower scores indicate a home performing better than the standard American home. A zero on the HERS index is given to a home demonstrating a net energy demand of zero (Polly et al. 2011) The HERS Index score can be described as a sort of mile per gallon rating for houses.

**FIGURE 1.** Geographical display of the residential units for data collection.



It provides prospective buyers and homeowners insight into how the home ranks in terms of energy efficiency.

The data were processed and collected through direct on-site visits. The research team organized meetings on-site where property managers and residents were approached with incentives for releasing information. The team collected the utility release forms and partnered with Wegowise, an on-line utility tracking platform, to monitor units and for research purposes only. As a result, two types of data were collected: the utility bills and the building's technical records. The utility bills were collected across one year from June 2013 to May 2014. Such data denote the actual amount of consumed electricity and the money paid to the utility company. The technical records include information about a home's location, area size, building design, mechanical systems for heating/cooling, mechanical system for water heating, insulation in the building shell, and lighting and appliance features. The technical records were later used in energy modeling to obtain the estimated energy use. Particularly, the following 11 categories of technical records were collected for energy modeling (Parker et al. 2012):

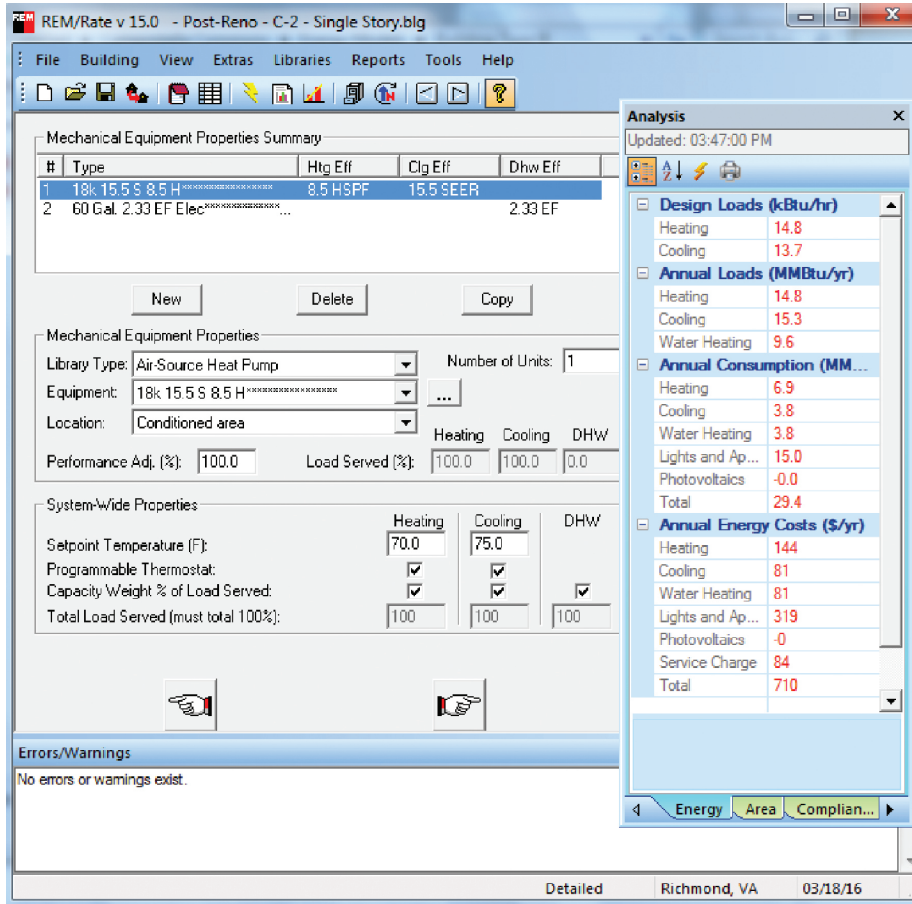
- Conditioned area
- Conditioned volume
- House type
- Air-source heat pump
- Water heating
- Ventilation system
- Programmable thermostat
- R-value
- Windows
- Infiltration rate
- Lighting and appliances

### **3.2 Analysis**

In an effort to accurately assess the residential energy performance, the researchers employed statistical analysis to compare the sample's observed annual energy consumption, estimated annual energy consumption, and the location-based average energy consumption. Data of the observed energy consumption are from the collected utility bills. Data of the estimated energy consumption are from the energy modeling of collected technical records. The average energy consumption information is retrieved from public data sources. Finally, data from a total 202 qualified samples were used in the statistical analysis due to missing values.

In obtaining the estimated energy use, the researchers input the technical records into industry-standard energy models of the intended design and construction on energy performance for each occupant household unit. Model estimates of utility costs are per unit for designs and provide a nominally estimated design effect. Residential energy modeling and analysis was performed in the REM/Rate software (see Figure 2), which calculates heating, cooling, hot water, lighting, and appliance energy loads, and consumption and costs for new and existing single and multi-family homes. Climate data which are available for cities and towns throughout North America are also incorporated into the energy modeling. The software has been widely adopted in the building research and energy auditing practice (Mosteiro-Romero et al. 2014; Sawhney et al. 2002; Walsh et al. 2003), and thus is believed to be an efficient home energy analysis tool.

**FIGURE 2.** Interface of REM/Rate software used for energy modeling.



Analytical techniques include *t*-test, correlation analysis, and linear regression. Particularly, a linear regression technique is used to identify the correlation between energy consumption and building technology. The regression equation is described in Eq. 1, as follows:

$$C = \beta * T + \varepsilon \quad (1)$$

where  $C$  is the per-unit energy consumption,  $T$  is the green building technology level, which is represented by the HERS index,  $\beta$  is the coefficient, and  $\varepsilon$  is the error term. In an effort to accurately assess the residential energy consumption and efficiency, the researchers collected two sources of energy data and analyzed them, as previously discussed. Each HERS certification acts as an official verification of energy performance by the U.S. Department of Energy and the U.S. Environmental Protection Agency. The HERS certification provides a HERS index which ranges from 0 for a net-zero building and 100 for a conventional reference building (Mosteiro-Romero et al. 2014).

The researchers assess the economic influences by computing the financial savings. The following benefit equation (Eq. 2) converts the annual energy savings into monetary values, and the rate equation (Eq. 3) leads to the saving rate that indicates the ability of energy saving:

$$S = E_o - E_a = \sum_{i=1}^n (C_{oi} - C_a) P_i \quad (2)$$

$$R = \frac{E_o - E_a}{E_a} = \frac{\sum_{i=1}^n (C_{oi} - C_a) P_i}{\sum_{i=1}^n C_a \cdot P_i} \quad (3)$$

where,  $S$  is the yearly financial savings (in U.S. dollar),  $R$  is the ratio of energy saving,  $E_o$  is the observed yearly energy expenditures,  $E_a$  is the average energy expenditures,  $C_{oi}$  is the observed yearly energy use for the  $i$ th residential unit, the  $C_a$  is the location-based average home energy usage, and  $P_i$  is the  $i$ th unit based utility price. The price was converted into a 2014 dollar value to mitigate the influence from inflation of buying power.

## 4. RESULTS

### 4.1 Overall Home Energy Consumption

Table 1 summarizes annual energy consumption of units with complete records in the sample ( $n = 202$  residential units). The estimated energy consumption is simulated based on each unit's specific building systems. The authors expected units to be energy efficient after adopting green building standards. Results from energy simulation show an overall energy consumption of 8,000.1 kWh per unit per year, lower than the statewide average of 12,204 kWh. Moreover, the estimated energy consumption for divisions by construction type and occupant type are less than the state average: new units 7,439.6 kWh, renovated units 8,424.1 kWh, units for senior residents 7,245.4 kWh, and the units for non-senior residents 8,409.1 kWh. Results from variance analysis indicate that new developments and non-senior units contain higher variability in energy usage.

Interestingly, observed energy consumption is also lower than estimated. Results from statistical analysis (Table 1) show that the observed energy consumption is 6,819.7 kWh per unit per year, indicating 1,180.4 kWh lower than the estimation. Such paired difference is statistically significant at a 99% confidence level ( $t = -5.07$ ,  $p < 0.001$ ). Moreover, data analysis also indicates significant reductions of energy consumption at a 99% level in the following building divisions: renovated units (2,065.0 kWh,  $t = -7.44$ ,  $p < 0.001$ ), units for senior residents (769.9 kWh,  $t = 02.73$ ,  $p = 0.008$ ), and units for non-seniors (1,403.5 kWh,  $t = -4.33$ ,  $p < 0.001$ ).

While Table 1 lists the paired differences of estimated and observed energy consumption, Figure 3 plots these data. In the plot, a coordinate with positive value (above 0) on the  $y$ -axis denotes a unit with higher observed energy consumption, while a coordinate with negative value (below 0) denotes a unit with lower observed energy consumption. Results show that the mean difference is negative, which confirms reduced energy consumption in a real-world setting of observed usage. Figure 3 also illustrates the variability of energy performance across units. While the maximum variance is substantial, either positive or negative, for both new and renovated units, these outliers seem unlikely to be associated with building conditions, design, and construction. Rather, the authors posit that the variance is a result of differing residential behaviors (Ouyang and Hokao 2009; Zhao et al. 2016).

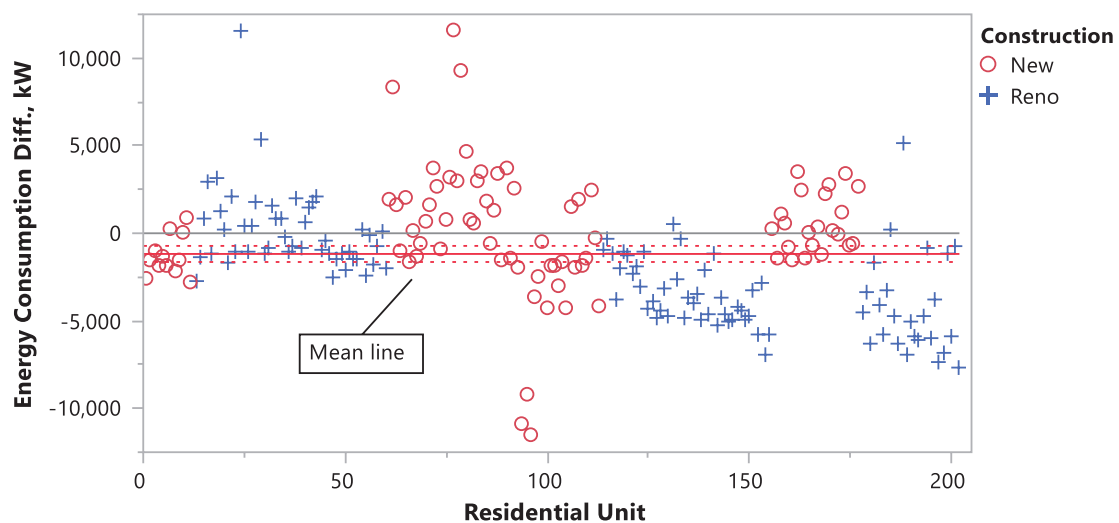
**TABLE 1.** Summary of annual energy consumption.

Division	Est. (kWh)	Obs. (kWh)	Diff. (kWh)	<i>N</i>	Std Err	<i>t</i>	<i>p</i>	Upper 95%	Lower 95%
Overall	8,000.1	6,819.7	-1,180.4	202	233.0	-5.07**	<0.001	-720.9	-1,639.9
New	7,439.6	7,428.4	-11.2	87	362.9	-0.03	0.9755	710.2	-732.6
Renovated	8,424.1	6,359.1	-2,065.0	115	277.7	-7.44**	<0.001	-1,514.9	-2,615.0
Senior	7,245.4	6,476.6	-769.9	71	281.7	-2.73**	0.008	-207.1	-1,331.6
Non-Senior	8,409.1	7,005.6	-1,403.5	131	324.4	-4.33**	<0.001	-761.7	-2,045.3

Note: Est = Estimated; Obs = Observed; Diff = Difference; Round-off errors may apply; \*\* = Significant at 99%.

#### 4.2 Level of Green Building Technology

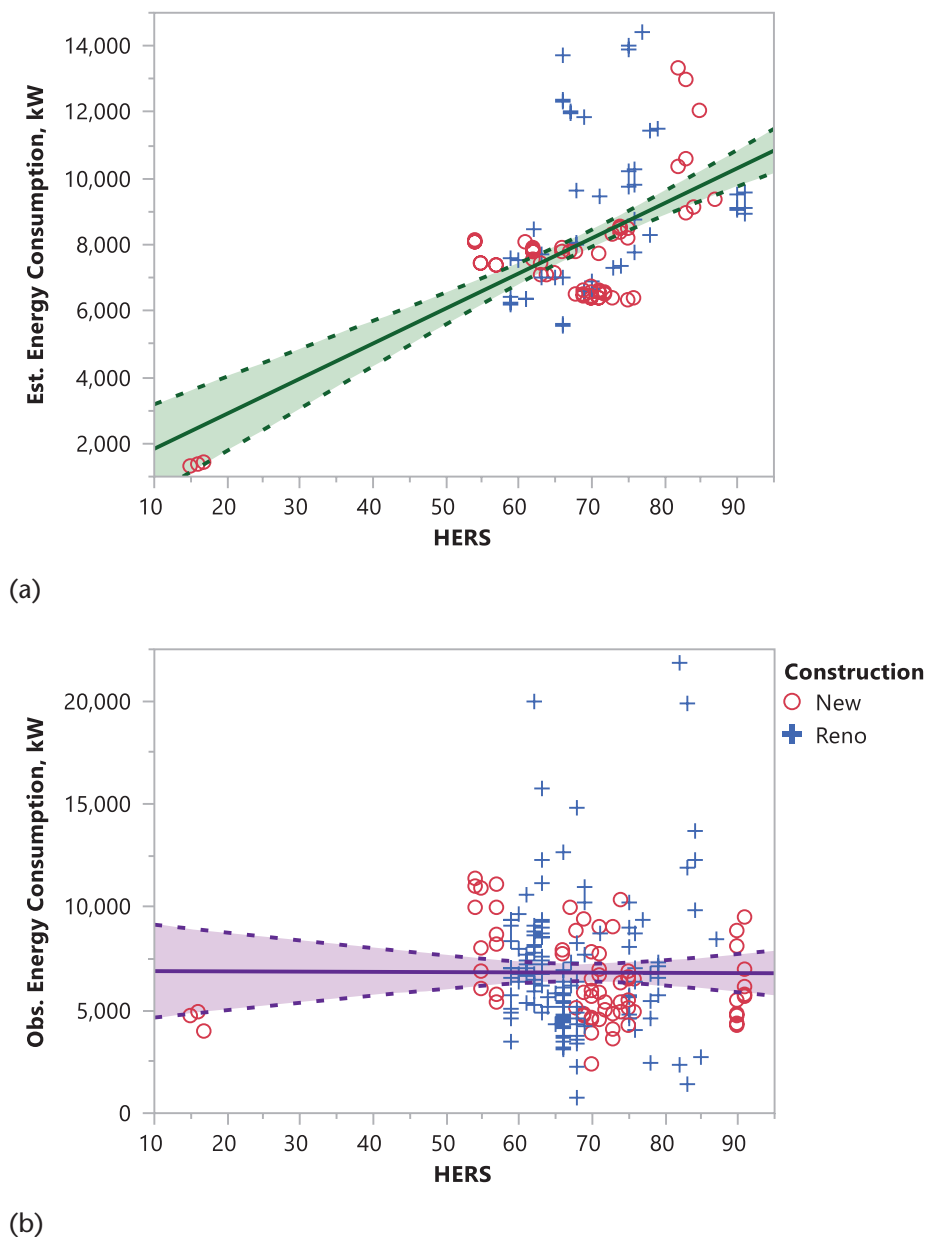
Figure 4 offers a visual representation of linear regression results for annual energy consumption (as the dependent variable) dependent on building technology (as the independent variable). In the analysis, building technology is represented by the unit's individual HERS Index score, an industry standard asset rating used to evaluate a home's performance compared to an equivalent home built to the 2004 International Energy Conservation Code (IECC). As an example, a HERS score of lower than 90 means that a home is 10% more energy efficient than standard new construction (current code-based construction). In our research, most HERS scores from the analyzed residential units range from 50 to 90, while three are less than 20 owing to net-zero energy building technology. The mean HERS score is 68.2. The HERS scores suggest that these units have incorporated appropriate building technology to improve energy performance, which

**FIGURE 3.** Plot of differences between the estimated and observed annual energy consumption.

was expected to be 31.8% (based on the average HERS score of 68.2) more energy efficient over standard new construction.

We also hypothesize that a lower HERS score (i.e., higher building technology) leads to lower energy consumption (i.e., higher energy efficiency). Coupling results from Figure 4 and Table 2, estimated energy usage positively correlates with HERS scores ( $\beta = 105.9$ ,  $R^2 = 0.30$ ). In other words, the lower the HERS score, the lower the estimated energy usage level and the higher the score the more energy efficiency is reduced (a negative correlation). The correlation is statistically significant at a 99% confidence level ( $F = 84.7$ ,  $p < 0.001$ ), confirming our

**FIGURE 4.** Linear regressions of annual energy consumption over building technology in (a) estimated; and (b) observed.



**TABLE 2.** Parameters in the linear regressions.

	Coefficient ( $\beta$ )	Disturbance ( $\epsilon$ )	$F$	$p$	R Squared	Mean Square Err
Estimated	105.9	780.6	84.7**	<0.001	0.298	1786.7
Observed	-1.2	6901.6	<0.1	0.950	<0.001	2997.7

Note: Round-off errors may apply; \*\* = Significant at 99%.

association between building technology and simulated energy performance. The R-squared value shows that only 30% of energy variance can be explained by building technology (i.e., HERS) and indicates additional predictors other than building technology. As a result of this strong correlation, we are able to posit the following formula that allows us to estimate annual energy consumption in kWh based on a 2010 HERS score:

$$\text{Estimated Energy Consumption (kWh/year)} = 105.9 \times \text{HERS} + 780.6$$

In contrast, results from observed energy consumption exhibit a non-linear correlation between building technology and observed energy performance. In other words, some units had excellent building systems according to HERS; however, they did not demonstrate accordingly remarkable energy efficiency. For example, in some units, the annual energy usage was estimated at less than 1,500 kWh per unit but observed at approximately 4,600 kWh per unit. Consequently, findings suggest that building technology might not be the only dominant factor for a home's energy efficiency and more variable than the HERS score itself.

### 4.3 Construction Type

Table 3 lists comparative values for energy consumption of new and renovated developments. Analysis indicates that the new residential homes are estimated to have lower energy usage (7,439.6 kWh) than renovated homes (8,424.1 kWh). Such a difference between new and renovated units is significant at a 99% level ( $t = 3.464$ ,  $p < 0.001$ ). On the contrary, observed results indicate new units use more energy (7,428.4 kWh) than renovated units (6,359.1 kWh). The difference in observation is statistically significant at a 95% level ( $t = -2.466$ ,  $p = 0.015$ ).

**TABLE 3.** Comparison of annual energy consumption by construction type.

	Construction Type	Mean (kWh)	Std Err	Upper 95%	Lower 95%	Diff. (kWh)	$t$	$p$
Estimated	New	7,439.6	187.4	7,812.1	7,067.1	-984.5	3.464**	<0.001
	Renovated	8,424.1	213.6	8,847.3	8,000.9			
Observed	New	7,428.4	358.9	8,141.8	6,715.0	1,069.3	-2.466*	0.015
	Renovated	6,359.1	243.5	6,841.4	5,876.8			

Note: \* = Significant at 95%; \*\* = Significant at 99%.

The finding confirms the important role of construction type on energy efficiency. The finding also suggests that while new units are expected to be higher in energy efficiency (a clean slate for designing and constructing the unit); in fact, renovated units can achieve better energy performance. It is also important to note that new units in our sample included a larger number of families with more than one person.

#### 4.4 Occupant Type

Table 4 lists comparative values for energy consumption between senior and non-senior occupants. Analysis indicates that in both estimated and observed usage, units designed for senior residents consume less energy than those for non-senior residents. Estimated energy usage for seniors is 1,163.7 kWh less per year while observed usage is 529.0 kWh less per year. According to building simulation models, senior units should have significantly lower energy consumption ( $t = 4.238$ ,  $p < 0.001$ ). However, observed usage does not support the simulation indicating less significance in the difference ( $t = 1.375$ ,  $p = 0.173$ ) between senior and non-senior occupants. Results suggest that the design of the occupant type currently impacts a unit's energy consumption less than expected.

#### 4.5 Energy and Financial Savings

Table 5 summarizes the annual energy and financial savings as a result of the incorporation of building energy efficient technologies. Results indicate that per-unit energy savings are 5,384.3 kWh per year, which is 28.1% greater than estimated. Combining the average utility rate of \$116.7 per 1000 kWh (U.S. Energy Information Administration 2014) for Virginia, such savings equal \$628.4 per year. Findings suggest that the per-unit savings are estimated to be 34.1%, yet are observed at an even larger amount of 43.7%.

The researchers also calculated the savings by conditioned area (in square footage), considering that the per-unit data might not necessarily provide a complete picture of energy usage. Analysis indicates that the actual energy savings are 6.8 kWh per square foot (equals to 73.2 kWh/m<sup>2</sup>), which equals to \$0.80/sf (equals to \$8.6 per m<sup>2</sup>). These resulting savings were then compared with national energy usage data (U.S. Department of Energy 2011). Results of saving rates from Table 5 show that area-based savings are as much as 43.4% of new standard construction for multifamily homes.

Overall, findings from per unit and per area savings are highly consistent, both of which demonstrate that the units are more than 40% energy efficient than standard new construction built to IECC requirements.

**TABLE 4.** Comparison of annual energy consumption by occupant type.

	Occupant Type	Mean (kWh)	Std Err	Upper 95%	Lower 95%	Diff. (kWh)	<i>t</i>	<i>p</i>
Estimated	Senior	7,245.4	190.4	7,625.1	6,865.7	1,163.7	4.238**	<0.001
	Non-Senior	8,409.1	197.8	8,800.5	8,017.7			
Observed	Senior	6,475.6	252.1	6,979.5	5,973.7	529.0	1.367	0.173
	Non-Senior	7,005.6	293.6	7,586.5	6,424.7			

Note: \*\* = Significant at 99%.

**TABLE 5.** Summary of annual energy and financial savings.

	Savings per Unit			Savings per Sq. ft.		
	Energy (kWh)	Savings (\$)	Rate (%)	Energy (kWh)	Savings (\$)	Rate (%)
Estimated	4,203.9	\$490.6	34.1	5.3	\$0.60	34.1
Observed	5,384.3	\$628.4	43.7	6.8	\$0.80	43.4

## 5. DISCUSSION

### 5.1 Homeowners and Energy Expenditures

According to Adomatis (2010), the concept of ensuring performance in housing contains roots in the business concepts of quality and customer satisfaction. Performance is integral to the assurance of quality in housing, which might, in turn, lead to satisfaction. Quality is subjective, though, and may be understood differently by consumers within and across markets. Summary measures of performance can help reduce speculation of quality for a product/service, a major barrier to the adoption and diffusion of green technology.

Increasing home operating cost is a major factor in assessing building performance. Residents finding themselves on the threshold of affordability can see their energy costs push housing expenditures beyond the normally accepted 30%. The globally trending rise in energy consumption and cost will further the financial burden placed on residents if energy costs escalate at the projected exponential rate (DOE, 2011). Additional hardships are realized because month-to-month and year-to-year energy costs are not constant. As household energy demands fluctuate, dependent on year-to-year weather conditions, so do monthly energy costs. This erratic monthly variance in the percentage of income allotted for housing is destabilizing to family finances.

Results from this study suggest that the actual energy savings are 6.8 kWh per square foot (equals to 73.2 kWh/m<sup>2</sup>), which equals to \$0.80/sf (equals to \$8.6 per m<sup>2</sup>). Compared with national energy usage data (DOE, 2011) results show that area-based savings are as much as 43.4% of new standard construction for multifamily homes. Further, findings from per unit and per area savings are highly consistent, demonstrating more than 40% energy efficiency than standard new construction built to 2004 IECC requirements.

The impact is especially important to the low-income household. A low-income household is one that earns less than half of the median income for their area. For these households, the cost of housing alone can take a significant portion of their gross income within the generally accepted rule that housing cost should ideally not be more than 30% of one's gross income; it is often the case that low-income households spend more than 30% of their gross income on housing and associated operating cost.

All households are affected by energy expenditures and the rising cost of energy. However, not all households have the financial means to simply pay more for their required energy expenditures. Therefore, those households with low incomes will be burdened the most by future inflation. In examining the role energy expenditures play in housing affordability, Lee et al. (1995) calculated that energy cost burden accounted for 13% of housing expenditures for households above the low-income level. Comparatively, for a low-income household 25% of

their total housing expenditures were dedicated to energy. Of the total energy consumed, over 40% was consumed by space heating and air conditioning.

## **5.2 Housing Policy and Affordability**

Findings of energy performance comparison within the concept of green building standards provide quantifiable evidence for policy makers in the realm of housing and development. Whether it is a rental payment or a mortgage payment, housing costs make up a large percentage of Americans' monthly expenditures. The U.S. Department of Housing and Urban Development (HUD) uses residents' ability to afford monthly expenditures, such as housing, to determine policies for housing assistance and affordable housing creation. The provision of affordable housing is vital for promoting vibrant communities and strong economies. The relationship between energy costs and housing affordability has been long established in the research (Lee et al. 1995) and in public policy (e.g. LIHEAP, weatherization, housing subsidy utility allowances, DOE-HUD initiative on energy efficiency in housing). A basic internet search for "affordable housing" and "energy efficiency" produces 1,450 matches in the Energy Citations Database and 788 matches in peer-reviewed publications. Although the impacts of the weatherization program have been extensively documented, the benefits of energy efficiency in new and renovated affordable housing are typically assumed and have not been rigorously analyzed.

Throughout history, the U.S. has used different approaches to alleviate housing payment burdens for low-income households. Federal government programs include public housing, housing choice vouchers, community development block grants (CDBG), and most recently, the Low-Income Housing Tax Credit (LIHTC). Today, the LIHTC is the largest low-income rental subsidy in the U.S and is an item of the Internal Revenue Code, not a federal housing subsidy (Schwartz 2011). To understand the impact housing policies can have on affordable housing, it is essential to understand the role of housing policy within the LIHTC. Since the income of renters in the LIHTC program is significantly below the Area Median Income (AMI), financial savings could heavily affect their annual income. For a typical America household, the residential energy cost expenditure (e.g., for heating and cooling) approximately accounts for 3–5% of their gross annual income. Combining average expenditures with these savings, units in the Virginia LIHTC are significantly lessening household energy burden (40–46% in some cases) due to energy efficient units.

Further, while housing expenditures applied toward a mortgage (including additional construction cost for higher quality) build equity, energy expenditures add nothing to a family's accrued value of ownership in a property. It is easy to become energy insecure when a household experiences at least one of the following in a year (Elevate Energy 2014): they are threatened by utility shutoff; one of their utilities is shut off or they are refused delivery of a heating fuel; they go with a day of no heat or cooling because of the inability to pay bills; or they are forced to use a cooking appliance as a source of heat.

## **5.3 Residential Building Industry**

The impact that energy efficient building design, construction and 3rd party verification has on housing costs plays a key role in determining the future of EE policies in green building standards. By studying 3rd party verified rating systems and their integration of energy efficient building practices, there is now a greater understanding of predicted vs. measured energy efficiency in high-performance residential buildings. Results from this study suggest observed energy savings is 5,384.3 kWh per year (28.1% greater than estimated) with savings equal

\$628.4 per year on average. While per unit savings are estimated to be 34.1%, they are observed at an even larger amount of 43.7%.

In general, housing is constructed as inexpensively as permissible for its market type by meeting the minimum requirements for current code standards. This is done in order to keep first costs low, thus ensuring clients' financial accessibility and maximum profitability for developers and homebuyers alike. In the past, little consideration was given towards energy efficiency and the additional expense of operation (primarily conditioning cost) that result from building to minimum standards. Such practices have been found to be common when attempting to create housing accessible to low-income households. As a result, housing built to a target cost point with short-term financial motives and to minimum standards is often not as energy-efficient as it could be. This lack of energy efficiency creates a higher operating cost when compared to high-performance construction methods and materials.

For example, a green building certification under EarthCraft Virginia requires that a development meet basic criteria: 1) meeting energy modeling performance goals, 2) meeting minimum worksheet requirements and points thresholds (variable depending on new/renovation or single family/multifamily, 3) pass all required inspections/site visits including air sealing, pre-drywall, and final testing (including enclosure and duct leakage testing). According to EarthCraft, the additional construction costs for a certified home are no more than 3% higher than that of traditional construction. EarthCraft Virginia maintains that homes built to their specs are in actuality cheaper when factoring in long-term energy savings. A recent report by the Southface Energy Institute (Roberts et al. 2016) suggests that the green developments are performing better than the non-green developments in terms of construction and development costs, energy efficiency and utility costs and satisfaction.

#### **5.4 Building Energy Code Adoption**

Results from this study suggest that not only does the actual average energy use per unit vary considerably, the estimated energy use of design and construction modeling varies in the sample as well. Estimated model average variability suggests that design and construction for energy efficient units could be performed within tighter values across the sample, which could result in increased unit efficiency on average. Green building rating systems utilize the most current IECC provisions developed by the International Code Council as a minimum performance benchmark. In the U.S., state or local jurisdictions decide the year of building code adoption (Zhao et al. 2015), which leads to the variability of building codes. In other words, some states or cities adopt newer codes while others use older codes. For example, the HERS reference home is based on IECC version 2004, using the language "standard new home, which meets the current industry standard for home energy efficiency. Virginia has adopted the 2012 IECC as of this study while the developments included are closer to 2009 IECC requirements. Since residential energy codes have increasingly become prescriptive over the last 10 years, findings from this study suggest that there could be an opportunity to utilize performance driven methodologies to more affordably meet the goals of future energy codes.

## **6. CONCLUSION**

This study investigates energy consumption and savings for energy efficient housing units as a result of adopting green building standards in the U.S. Towards this goal, researchers analyzed data on 202 residential units in the State of Virginia with complete records of simulated energy usage, observed energy usage, and incorporated energy efficiency technologies across one year

through utility records. The sample units included varying combinations of construction type (new and renovated) and occupant type (senior residents and non-senior residents). Results from this work have identified a significant reduction in energy consumption at 43.7% per unit or 43.1% per square foot (i.e., 0.093 m<sup>2</sup>), which indicate a high level of energy efficiency achievement. The results have also identified excellent financial savings due to energy efficiency technology at \$628.4 per unit or \$0.80 per square foot (i.e., \$8.6 per m<sup>2</sup>) in a year, which accounts for up to 2% of the household annual income or 46% of energy cost expenditures for an American home. Such findings are different from previous work which estimated that using high-performance energy design and construction technologies would save 25–30% of energy use over standard new construction practice. Moreover, findings suggest that construction type is a significant factor to a housing unit's energy efficiency, while the building technology is not the only dominant factor to a house's energy efficiency.

The findings contribute to the body of knowledge in three aspects: (1) simulated energy usage is higher than actual energy usage; (2) energy modeling via simulation tools is accurate for newly constructed buildings only; and (3) energy modeling, especially for existing buildings, is not accurate due to largely varying occupant behaviors. The findings also provide implications for policy makers by suggesting a rigorous quantification of gross and net economic impacts of energy efficient housing and by distinguishing energy usage differences through estimated, actual, energy efficiency technology and behavior influenced by development type and purpose.

The findings also indicate an opportunity for research to inform and calibrate energy code moving forward. Estimated model average variability suggests that design and construction for energy efficient units could be performed within tighter and more consistent values across the sample, which would result in increased overall unit efficiency. Regarding energy use, sample groups, such as new versus renovated units, and senior versus non-senior, contain internal variability while not ranging far from the overall sample average suggesting common factors to the affordable housing population. Variability is not increased by square footage, yet the number of people in the unit does seem to affect use. Research, therefore, suggests an opportunity for improved modeling tools.

This research has limitations. One limitation pertains to the difficulty in housing resident energy releases during data collection. The team, therefore, had an alternate plan for this possibility. When on-site collection processes did not work as planned, property managers were also asked to anonymously collect surveys left for residents. These releases collected by property managers constituted approximately 10% of all releases collected. Another limitation pertains to our sample that only reflect the energy efficiency of the multifamily houses within the affordable rental stock. The findings may not imply the energy use for commercial buildings.

Future work could extend this research as well. This work has found the existence of multiple impact factors, other than building technology, which critically influences a housing unit's energy usage. Research could benefit policy makers through further investigation of observed variables and how they impact residential energy efficiency. Another direction will be more investigation into a policy's impact on home builders, construction costs, and the correlation to savings from reduced utility bills.

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Virginia Center for Housing Research

# **Sustaining Energy Efficiency: Longitudinal Evidence of Virginia's Low-Income Housing Tax Credit Properties**

A HIGHLIGHT REPORT FOR HOUSING VIRGINIA | AUGUST 2017

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Andrew McCoy, PhD  
Director  
Virginia Center for Housing Research  
Professor, Dept. Building Construction  
Virginia Tech  
[andrew.mccoy@vt.edu](mailto:andrew.mccoy@vt.edu)

Dong Zhao, PhD  
Assistant Professor  
Dept. Construction Management  
Michigan State University  
[dzhao@msu.edu](mailto:dzhao@msu.edu)

Frederick Paige, PhD  
Assistant Professor  
Dept. Civil & Environmental Engineering  
Virginia Tech  
[freddyp@vt.edu](mailto:freddyp@vt.edu)

Philip Agee  
PhD Student  
Dept. Industrial & Systems Engineering  
Virginia Tech  
[pragee@vt.edu](mailto:pragee@vt.edu)

Yunjeong (Leah) Mo  
PhD Student  
Dept. Construction Management  
Michigan State University  
[moyunjeo@msu.edu](mailto:moyunjeo@msu.edu)



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## Executive Summary

This report shares findings from a multi-year study that measured the energy performance of Virginia's green building multifamily housing stock. Over the last ten years, the Virginia Housing Development Authority (VHDA) has utilized green building rating system incentives as a policy vehicle in the Low-Income Housing Tax Credit (LIHTC) program to encourage energy efficiency (EE) in the affordable rental stock in Virginia (Climate Zone 4). The research addresses key issues related to EE and affordable housing through the measurement of actual, unit-level energy use in 237 apartments across 15 developments. Data are used to evaluate the effects of year to year operation, climate and behavior on energy use. Data, analysis and findings focus specifically on facilities constructed and certified to the EarthCraft Multifamily (ECMF) rating system in Virginia, one of the only datasets currently available that allows for this type of inquiry. As a second component of the study, development cost data were analyzed for 24 developments containing 1,351 apartments to compare the cost for building green versus non-green. Findings suggest VHDA's green building incentives in the LIHTC program have been successful in promoting affordable housing development that saves residents on average 45% on their annual energy costs at little cost difference compared to non-green housing.

## Executive Takeaways

Findings suggest the following executive take-a-ways about energy and development cost in the affordable rental stock in Virginia's LIHTC program:

### Energy Use

- ✓ VHDA's green building incentives in the LIHTC program have been successful in promoting affordable housing development that saves residents on average 45% on their annual energy costs at little cost difference compared to non-green housing.
- ✓ Over 3 years, residents of sampled LIHTC units are saving more energy than estimated during design, saving more energy than observed in year one ( $Y_1$ ) and saving more energy than new standard construction estimates.
- ✓ Over 3 years, findings continue to indicate a significant reduction of energy costs for LIHTC residents. From low-income to extremely low-income housing units, residents can save between 3.1 and 8.3 percent of total annual housing costs from energy efficiency respectively.
- ✓ Over 3 years, the average per unit energy use intensity (EUI) is 55% more efficient than the National average and 43% more efficient than the Virginia average for multifamily rental housing.
- ✓ Over 3 years, building technology and resident behavior continue to be strongly correlated, yet fewer variables remain significant in reducing energy consumption.
- ✓ Research suggests that education on high performance housing (HPH) technologies is an opportunity for significant energy usage and cost savings. Residents that reported receiving education on their apartments had a lower average energy usage monthly and annually (over 3 years) by almost 15% (14.8 %) and a lower energy bill by \$10.56 per month.

## Development Costs

- ✓ The difference in the total cost between green and non-green LIHTC developments is not statistically significant nor does cost statistically correlate to energy usage in the unit.
- ✓ Data indicate a higher average total cost for non-green developments of 6.2% or \$7.15 per square foot compared to green developments. Data for LIHTC green developments indicate a lower average cost by 13% or \$10.08 per square foot in direct or “hard” costs and a higher average by 6.9% or \$2.93 per square foot in indirect and soft costs.
- ✓ Green building consultant fees represent \$0.36 per square foot or 0.38% of Total Development Costs. These fees do not appear to be a main contributor to higher soft costs in green developments sampled.
- ✓ The 3 year energy usage study results did not indicate a significant correlation between development costs and energy usage. Green buildings that were low cost to build realized just as much energy savings for residents as higher cost green buildings

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## List of Definitions

**Average Monthly Energy Usage:** Average Monthly Energy Usage refers to actual kilowatt-hours (kWh) of energy used by residents per month averaged across the entire sample.

**EarthCraft:** EarthCraft is a green building certification program that serves the Southeastern United States. EarthCraft has adapted over the years to address new challenges in the Southeast's built environment. Over the course of the program's 18 year history, more than 40,000 homes, multifamily units and light commercial spaces have been certified. EarthCraft Multifamily (ECMF) is the basis for the analysis in this report.

**EUI:** (Energy Use Intensity) EUI is a measure of energy usage per square foot per year (kBtu/sq ft./Yr.) at the site (as opposed to source). EUI is a common energy use normalization method that allows for the comparison of buildings with different square footages. EUI also known as a unit's "average annual energy footprint."

**EUI Site Average:** EUI site average is a measure of energy usage per square foot per year across a development.

**PPI:** PPI refers to the "Producer Price Index." According to the US Bureau of Labor Statistics, PPI "measures the average change over time in the selling prices received by domestic producers for their output." For analysis of costs to produce a building in this work, we use the PPI, as opposed to the CPI or "Consumers Price Index." According to the US Bureau of Labor Statistics, CPI "examines the weighted average of prices of a basket of consumer goods and services, such as transportation, food and medical care. It is calculated by taking price changes for each item in the predetermined basket of goods and averaging them." For analysis of costs of energy consumption in this work, we use the CPI.

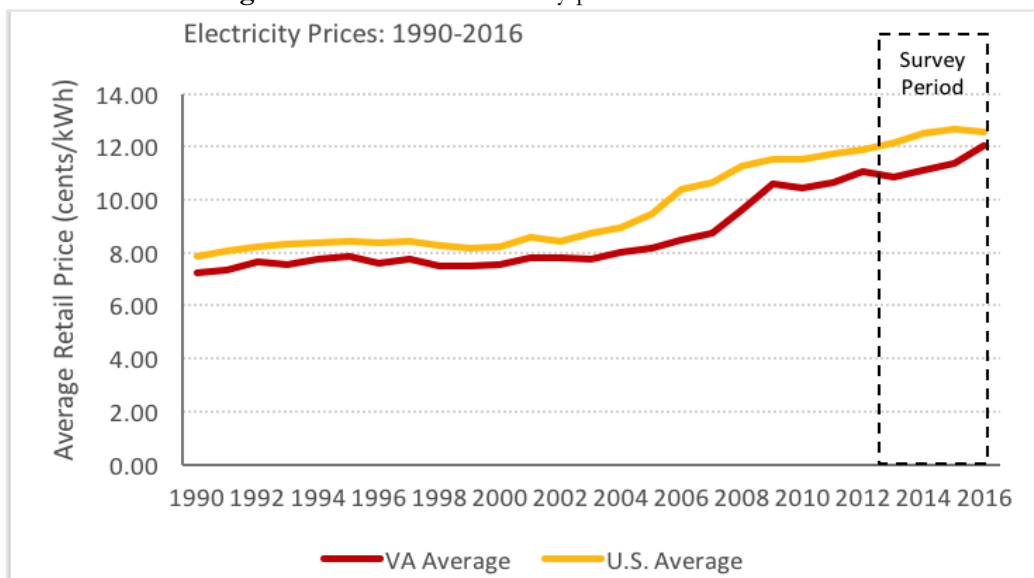
## Introduction

Buildings are complex socio-technical systems, yet housing professionals often perform their work lacking a formal post-occupancy feedback process that informs the goals for building performance. The industry has an energy efficiency information gap- it currently lacks verified energy performance standards and real-time data feedback post-occupancy for a residential project. Instead, energy use feedback is delivered to residents by static, non-salient and sometimes difficult to understand utility bills. These bills, representing the primary form of energy use feedback are made available often days, if not weeks after the energy was used by the resident. In sub-metered housing developments, builder-developers suffer from further informational and feedback lag. Gaps and lags in information create uncertainty for residents on fixed incomes and builder-developers investing in housing. This work reduces the energy efficiency information gap by providing empirical evidence of sustained energy use reductions and development costs following the use of a 3rd party verified energy efficiency program in multifamily housing.

## Background

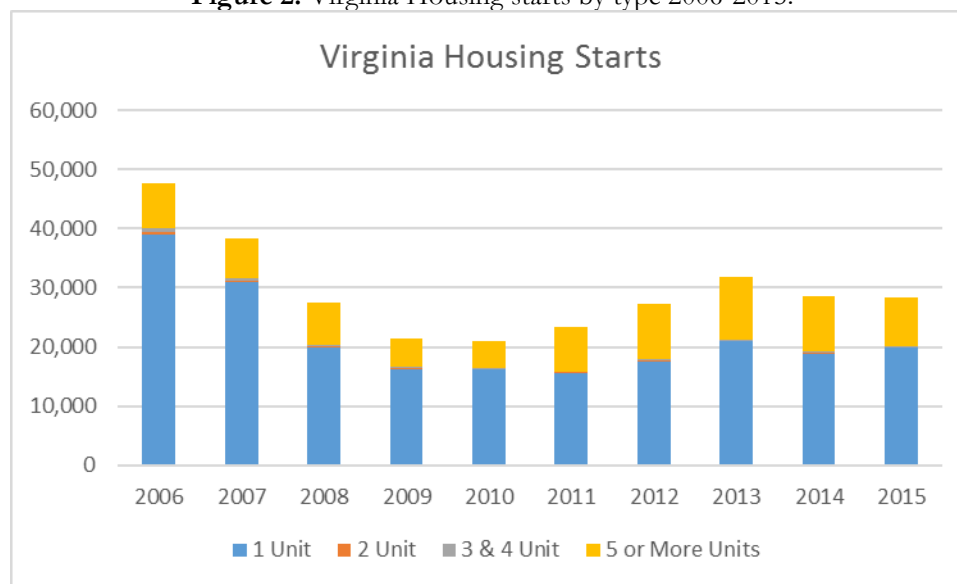
Figure 1 graphs residential electricity price (\$/kWh) trends for the United States and Virginia from 1990-2016. Virginia electricity pricing is trending with national pricing. Virginia electricity prices have increased by an average of 1.5% per year over 25 years and 3% annually over the last ten years.

**Figure 1.** Residential electricity price trends 1990-2016.



Based on these trends, Virginia LIHTC builder-developers could expect a 22.5-45% increase in electricity costs over the 15 year tax credit project compliance period. In tenant paid, sub-metered developments, the housing's affordability is directly impact by rising energy costs. If the electricity is sub-metered and paid by the resident, they are directly impacted by the raising electricity costs. Conversely, builder-developers that own properties with sub-metered, tenant paid utilities are indirectly impacted by the rise in electricity prices. The misalignment between electricity cost burden and building investment creates a split-incentive. A split-incentive<sup>1</sup> occurs when one party (builder-developer) invests in efficiency improvements, yet another party (the renter) receives the direct benefit of reduced utility bills. The split-incentive of builder-developer investment in energy efficiency with the tenant receiving the direct benefit has been described as a market failure and burden to widespread adoption of energy efficiency in multifamily housing. This market failure is important because multifamily housing production has been strong over the last ten years. Figure 2 indicates the number of housing starts in Virginia since 2006, also showing the percentage of 5 and more (multifamily) units as part of total housing production. The trend of rising electricity costs and multifamily starts creates a need to better understand post-occupancy building performance to help overcome the split-incentive in multifamily rental housing.

**Figure 2.** Virginia Housing starts by type 2006-2015.



Better alignment between occupant behaviors and performance goals of architecture, engineering and construction (AEC) professionals could benefit stakeholders throughout the residential supply-chain, leading

<sup>1</sup>ACEEE. (2009) Retrieved from <http://aceee.org/fact-sheet/multifamily-and-manufactured-housing-program>

to better informed project teams, greater market penetration of energy efficient buildings, reduced risk for housing providers and higher levels of user satisfaction. This study specifically reports statistical correlates of actual energy use, occupant behavior and technology in multifamily housing units across one and-three-year data. The work builds on previous work by the research team<sup>2</sup> (termed Study Y<sub>1</sub> hereafter) in year one which focused on 3rd party verified, affordable high performance housing (HPH) units and found significant direct and indirect effects of behavior and technology on energy efficiency.

The main objective of this research is to further study variability in the green building stock, including costs, energy usage and implications for educating residents of Virginia's affordable housing stock. We begin by appending data on energy efficient building technology and resident behavior variability (Study Y<sub>1</sub> data) in energy use with years two and three. We then collect and append Study Y<sub>1</sub> data with financial information on the cost variability of green versus non-green housing, setting a basis to motivations for an energy efficient property portfolio. Both sides of the equation will benefit through education from the resulting information.

Another objective of this research is to identify the impact of educational interventions that encourage EE in the affordable rental stock in Virginia through examining residential energy usage, technology and behavior in LIHTC developments. A LIHTC resident's motivation and ability to maximize the energy efficiency of their home is linked to their understanding of energy. Previous studies have shown linkages between personal pro-environmental behavior, such as efficient energy use, and level of education (Poortinga, Steg and Vlek 2004) (Nair, Gustavsson and Mahapatra 2010). The connection between the education and reduced energy consumption is a topic of debate, but targeted occupant education has been shown to be an effective method for reducing energy consumption (Delmas, Fischlein and Asenio 2013) (Zografakis, Menegaki and Tsagarakis 2008). Even for residents who are not financially incentivized to conserve energy have been motivated to develop energy saving behaviors through education (McMakin, Malone and Lundgren 2002). The research presents preliminary findings from educating Virginia's affordable housing residents on energy efficiency and aims to unpack correlates among three years of data on education of EE technologies versus those without education.

Uncertainty due to expected performance and initial cost of adoption often reduce the probability of realizing anticipated returns on housing innovation, promoting path dependency as builders primarily use proven technologies (Harvey 2013; Beerepoot and Beerepoot 2007; El-Shagi, Michelsen and Rosenschon 2014). For green building, there is mounting evidence that these gains are capitalized in the prices of residential buildings (Aroul and Hansz 2011; Bloom, Nobe and Nobe 2011; Dastrup et al. 2011; Kok and Khan 2012). Household

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<sup>2</sup> <http://www.vchr.vt.edu/wp-content/uploads/2015/02/Housing-VA-LIHTC-Study-Full-Report.pdf>

energy prediction is significant to the policy and strategy that affect energy use reduction, economic development, and environmental sustainability (Zhao et al. 2015) as well. Many studies have investigated buildings' energy performance and its associated factors such as construction technology, building enclosure, building envelope, heating, ventilating, and air-conditioning (HVAC) systems, indoor environmental quality, lighting and appliances, weather and occupant behavior (Tavares & Martin 2007). Few studies have focused on the relationship between construction cost and energy use.

### ***SAMPLE CHARACTERISTICS***

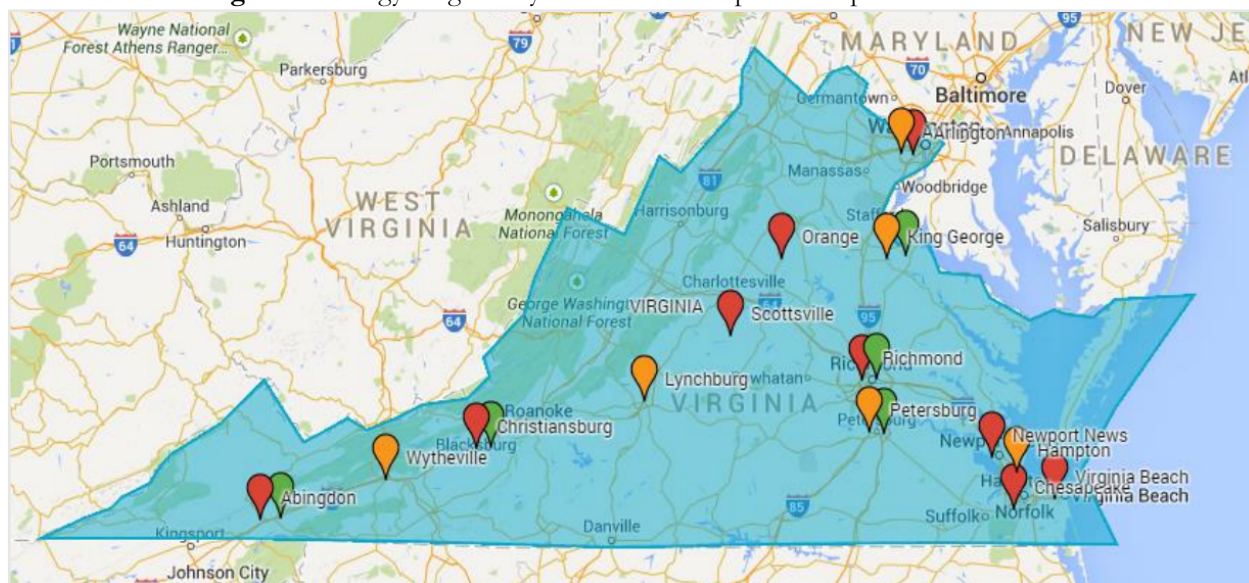
The sample utilized for the energy use component of this work is comprised of 15 LIHTC projects that were previously evaluated in Study Y1. Selection of each project for the energy use study included its location within the Commonwealth (Figure 3), EarthCraft certified by Viridian<sup>3</sup> (formerly EarthCraft Virginia) and constructed and/or renovated since 2009. The energy efficiency scope for new and renovation projects follow a design and construction process that balances performance goals and prescriptive requirements in the EarthCraft program. Project teams engage Viridian staff during the conceptual design phase for energy efficiency goal integration prior to applying for LIHTCs. Once funded and nearing a permit set of project documents, teams participate in a Design Review with Viridian staff, reviewing project details, system integrations and energy simulations. As the project is mobilized on site, Viridian Technical Advisors meet with on-site construction staff and subcontractors to review energy efficiency goals, provide 3rd party verification and perform diagnostic testing to confirm goals set during design are executed throughout construction process. The typical new construction project scope includes: enclosure air-sealing and testing, space conditioning duct sealing and testing, high efficiency equipment, appliances and lighting. The renovation projects in the sample can be described as deep energy retrofits, with 30-40% energy efficiency improvement goals achieved through a typical scope including enclosure air-sealing and testing, space conditioning duct sealing and testing, high efficiency equipment, appliances and lighting.

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<sup>3</sup> <http://www.viridian.org/>

## SAMPLE TYPES AND LOCATIONS

**Figure 3.** Energy usage study locations of sample developments and units.



Notes: red pins: Reno projects, orange pins: New Construction projects, green pins: Senior projects.

Previous work (Zhao et al., 2017) correlated the concepts of building technology, occupant behavior and energy consumption over one year from May 2013 to April 2014. The authors selected variables in computational analysis that correlated relationships among the concepts. Variables relevant to this work included: 1) observed annual energy consumption (ECo) to measure unit-level energy usage and 2) 11 variables to measure resident behaviors (for example, thermostat set points). Secondary analysis used observed energy use as the response variable (i.e., dependent variable) and the other 13 variables served as the predictor variables (i.e., independent variables) and which were distilled from the team's condensed literature review that characterized them as highly relevant to energy usage.

Study Y<sub>1</sub> indicated that technological advances in building systems directly contribute to 42% of energy efficiency. Behavioral factors, summer temperature setting, winter temperature setting, humidity setting, dishwasher usage, washer/dryer usage, and education on building systems contained quantifiable evidence supporting the hypothesis that building technology and resident behaviors interact with each other and ultimately affect residential energy consumption (Zhao et al., 2017). Now with three years of longitudinal energy use data, the current study (termed Study Y<sub>3</sub> hereafter) utilizes a similar mixed-methods approach to

understand changes in the relationships of building technology, occupant behavior and climate data over time for multifamily energy use from May 2013 to April 2016.

For the development cost analysis, researchers collected construction cost data from 24 developments totaling 1,351 multifamily units in Virginia. The cost sample is comprised of the 16 original Study Y<sub>1</sub> projects, as well as 8 non-green LIHTC projects built by a builder-developer that is still actively producing LIHTC housing in Virginia. Buildings were a mix of new construction and rehabilitation projects built between 1998 and 2012 as VHDA-funded LIHTC multifamily developments. Projects built as non-green were built prior to 2008, when the VHDA green scoring criteria was implemented. Projects represent a variety of geographic locations across the Commonwealth.

This work contributes to the knowledge around energy consumption, capital costs and paybacks by comparing actual costs over 15 years for non-green and green multifamily projects in the Virginia LIHTC program. The work also focuses on the latent relationship between construction cost and actual energy consumption in high performance housing. Results from this study reinforce the ability to use cost data and identify critical variables for energy prediction. The work will advance the information exchange around actual costs of green buildings and the ability to capitalize on possible gains while also identifying the need to address key barriers to EE technology diffusion in the housing market.

## Sample Methodology

It is important to note that the sample size changed from our previous, 1-year study to this study of energy usage in the LIHTC sample over 3 years. The sample size of the 1-year study was 207 observations and the following 3-year study contains 237 observations. The researchers collected the construction cost data from 24 developments totaling 1,351 multifamily residential units in Virginia. Table 1 provides an overview of the Energy Use, Cost Analysis and Energy Use + Technology + Occupant Behavior + Development Costs sample. Monthly energy consumption data were collected through a partnership with industry collaborators. The energy use data for each residential unit were averaged from May 2013 to April 2014. The average energy use per unit was normalized by the square footage of the unit similarly to the cost data normalization.

**Table 1.** Project sample summary.

	Energy Use		Cost Analysis		Energy Use + Technology + Occupant Behavior + Development Costs
	Y1	Y3	Green Developments	Non-Green Developments	Green Developments
Developments	15	15	16	8	9
Units	207	237	1159	203	197

For the sample reporting “education/training on building systems and energy,” we examined two education interventions among a total sample of 230 units in the following formats: 1) residents reporting no education and 2) residents reporting education by property managers upon signing a lease or receiving educational modules when signing utility bill release forms. Determining influences on the variability of energy usage by residents will inform policies for education and incentives.

The research team collected cost data per Development. Costs were based on project Final Cost Certifications (e.g. 8609 Application) submitted to VHDA and then sub-categorized by Construction Specifications Institute (CSI) divisions of work, including both the direct costs of facilities and buildings, and the indirect costs of sites and organizations. The construction cost, basic building information, and technical building data were collected in 2014 and 2015 as observed (actual) records through the aid of builder-developers.

While unit-level is the basis of analysis for much of the energy usage portion of this study, the sample size for the cost data analysis would have to be much larger to enable a unit level analysis. Instead, cost per square foot (\$/ft<sup>2</sup>) is the unit of analysis used in the cost data analysis. Similar to previous work (Trachtenberg et al. 2012) and due to varying methods used to report costs, the site construction and acquisition costs are not reported including: land, demolition and existing structure fees. The researchers removed non-residential costs; calculating cost per unit from dividing the total construction cost of all included units by the number of units in the development and cost per square foot from dividing total construction cost of all included units by total square footage of residential units only. Since projects were completed from 1998 to 2012, the construction cost data were adjusted using the Producer’s Price Index (PPI), for 2013 dollar value, as previously defined (Ang et al. 2007). Green developments generally contained larger unit sizes, resulting in a lower price per square foot. The researchers are not suggesting that the unit size differences in green and non-

green unit sizes are not dependent on green building, but may be driven by market conditions and/or LIHTC policy. The study uses a square foot analysis to normalize this difference. Average costs are analyzed at a total cost level and at a subcategory level unpacked between hard (direct) and soft (indirect) costs. Soft costs are further detailed into eight standard cost subcategories for each development.

Finally, to correlate energy use, technology, occupant behavior data and development costs we collected the monthly energy consumption data over the past three years for a sample of 159 residential units from nine developments located in nine cities (see Table 2). These 159 units are included in our sample, as opposed to our population, as they also align with available unit-level energy data. The researchers collected monthly energy consumption through a partnership with industry collaborators and averaged from January 2013 to June 2016. The average energy use per unit was normalized by the square footage of the unit. 38 instances (residential units) without electricity data were removed from the initial 197.

**Table 2.** Summary of green development cost sample

Development Code	Location	Cost Certification (Year)	Number of Units
D1	King George	2012	18 units
D2	Chesapeake	2012	32 units
D3	Richmond	2008	29 units
D4	Arlington	2011	5 units
D5	Orange	2012	19 units
D6	Scottsville	2012	13 units
D7	Richmond	2012	22 units
D8	Lynchburg	2011	14 units
D9	Hampton	2011	7 units

### **ENERGY USE NORMALIZATION**

Comparing the performance of developments and units is a critical component of this work. There are varying development types and sizes within the sample, so data normalization is necessary. Table 3 provides an overview of the Y<sub>3</sub> sample project type and resident population within the sample, as well as average development and unit sizes. Energy use data were normalized by dividing the annual energy use (converted

from kWh/yr to kBtu/yr) by the conditioned area of each unit (square footage of the apartment) to develop an Energy Use Intensity (EUI) value per apartment per site, reflecting the energy used per square foot per year or kBtu/ft<sup>2</sup>/yr. The application of site EUI metrics for building performance benchmarking is similar to the mile per gallon (MPG) rating system used in the automobile industry; providing stakeholders throughout the supply chain with a standardized performance metric. Site EUI is a common normalization method utilized to compare energy use across different building types, sizes and occupant populations.

**Table 3.** Y<sub>3</sub> energy usage sample per development type, resident type and average unit size

Division	Developments (N)	Units (N)	Residential Development Area (Avg. ft <sup>2</sup> )	Avg. Unit Size (ft <sup>2</sup> )
Overall	15	237	73,035	843
New	7	96	57,034	877
Renovation	8	141	73,408	816
Senior	5	89	36,405	732
Non-Senior	10	148	102,218	917

Nationally, site EUI is used by government agencies including the Department of Energy and Environmental Protection Agency, industry standards organizations such as ASHRAE (American Society of Heating Refrigeration and Air-conditioning Engineers), the American Institute of Architects (AIA), the 2030 Challenge and more recently to support city benchmarking policies in New York City and Austin, Texas.

## Key Takeaways

### *ENERGY USE OVER 3 YEARS*

- ✓ Over 3 years, residents of sampled LIHTC units are saving more energy than estimated in design and construction, saving more energy than observed in year one (Y<sub>1</sub>) and saving more energy than new standard construction estimates. Overall, Study Y<sub>3</sub> sampled units saved 40.3 % or 4,608.87 kWh and \$524.03 over 1 year and saved 45 % or 5,169.37 kWh and \$587.76 per year over three years versus standard new construction.

- ✓ Study Y<sub>3</sub> findings continue to indicate a significant reduction of energy costs for LIHTC residents. Regarding energy use, Study Y<sub>1</sub> data indicated a lower average energy cost of \$524 annually than new standard construction estimates<sup>4</sup> (New Standard Construction Est. Energy Use – Obs. Use Y<sub>1</sub>/ New Standard Construction Est. Energy Use). Compared to new standard construction estimates, Study Y<sub>3</sub> data indicate financial savings of \$49 per month or \$588 annually for LIHTC residents.
- ✓ While the Y<sub>1</sub> and Y<sub>3</sub> studies normalized energy cost data by using the same kWh price over the three years of the study, energy prices in Virginia have risen over this study period as described in the Background section of this report. If today's prices were used to calculate savings, the savings would be greater.
- ✓ From low-income to extremely low-income housing units, residents can save between 3.1 and 8.3 percent of total annual housing costs from EE respectively. Based on the 2015 HUD Income Limits for a 4-person family (\$78,400.00) in Virginia, savings equate to 3.1% of housing costs for low-income households, savings equate to 4.9% of housing costs for very low-income households, savings equate to 8.3% of housing costs for extremely low-income households.

**Table 4. Annual energy use (kWh) summary**

Division	Estimated Use		Measured Use	
	New Standard Construction Est. Energy Use (kWh Annually)	Est. Energy Use (kWh Annually)	Obs. Use Y <sub>1</sub> (kWh Annually)	Avg. Obs. Use Y <sub>3</sub> (kWh Annually)
Overall	11,428.57 (\$1,299.43)	8,000.10 (\$909.61)	6,819.70 (\$775.40)	6,259.20 (\$711.67)
New	10,628.00 (\$1,208.40)	7,439.60 (\$845.88)	7,428.40 (\$844.61)	6,914.40 (\$786.17)
Reno	12,034.43 (\$1,368.31)	8,424.10 (\$957.82)	6,359.10 (\$723.03)	5,799.60 (\$659.41)
Senior	10,350.57 (\$1,176.86)	7,245.40 (\$823.80)	6,476.60 (\$736.39)	6,270.00 (\$712.90)
Non-Senior	12,013.00 (\$1,365.88)	8,409.10 (\$956.11)	7,005.60 (\$796.54)	6,252.00 (\$710.85)

<sup>1</sup>Note: Est = Estimated; Obs = Observed

<sup>2</sup>Note: costs calculated at price of \$0.1137/kWh, which was the VA state average for 2015.

<sup>4</sup> Estimated using RESNET approved energy simulation software; REM/Rate - [http://www.resnet.us/professional/programs/energy\\_rating\\_software](http://www.resnet.us/professional/programs/energy_rating_software)

- ✓ Sampled new construction units saved 30% or \$363.79 over 1 year and saved 32.4% or \$422.23 over 3 years versus standard new construction.
- ✓ Sampled renovation units saved 47.2% or \$645.28 over 1 year and saved 51.8% or \$708.90 over 3 years versus standard new construction.
- ✓ Sampled senior units saved 37.4% or \$440.47 over 1 year and saved 39.4% or \$463.96 over 3 years versus standard new construction.
- ✓ Sampled non-senior units saved 41.7% or \$569.34 over 1 year and saved 48% or \$655.03 over 3 years versus standard new construction.

### ***ENERGY USE INTENSITY (EUI) OVER 3 YEARS***

- ✓ Over 3 years on average, all building types in the sample are statistically correlated with reduced energy usage. Of these building types, and similar to energy usage findings, new construction has the least significant correlation, suggesting areas for future work in design and construction.
- ✓ Overall, sampled units contain an energy use intensity 20% less than estimated.
- ✓ Sampled new construction units contain an energy use intensity 8.4% less than estimated.
- ✓ Sampled renovated units contain an energy use intensity 26.2% less than estimated.
- ✓ Sampled senior units contain an energy use intensity 17% less than estimated.
- ✓ Sampled non-senior units contain an energy use intensity 21.2% less than estimated.

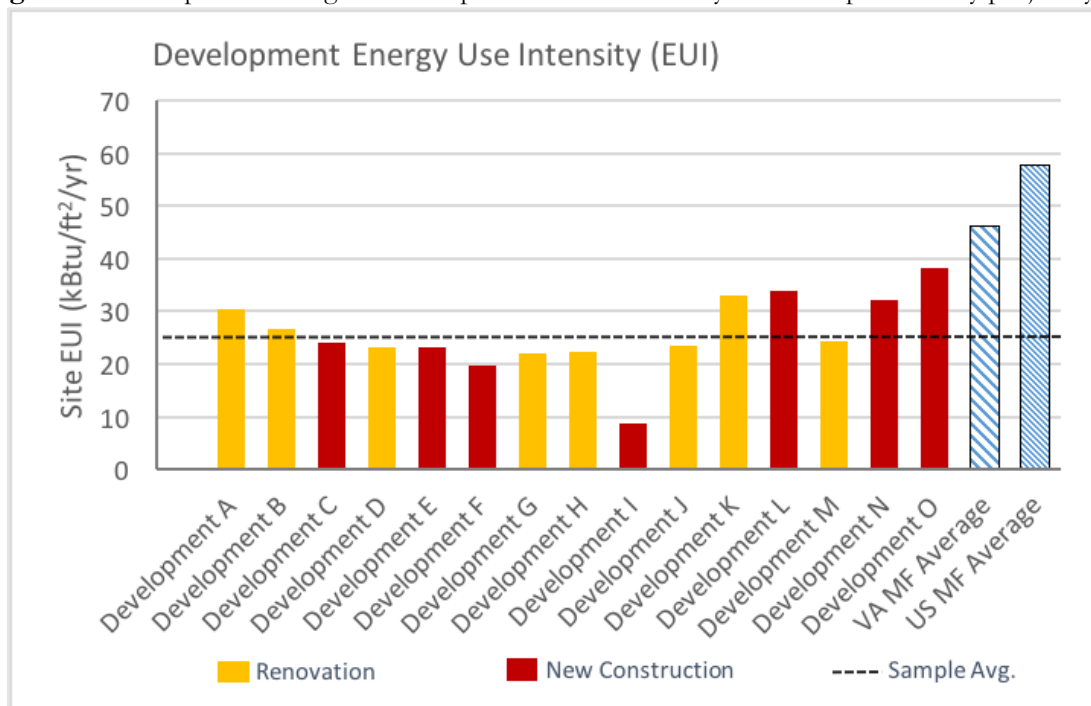
**Table 5. EUI summary table**

Division	Est. EUI	Obs. EUI	Diff. EUI	N	Std Err	t	p	Upper 95%	Lower 95%
Overall	32.25	25.94	6.31	237	.78	8.11	<0.001**	7.84	-4.78
New	29.75	27.23	2.52	96	1.33	1.89	.031	5.17	-.13
Renovated	33.95	25.05	8.89	141	.88	10.10	<0.001**	10.63	7.15
Senior	34.28	28.42	5.86	89	1.16	5.05	<0.001*	8.16	3.55
Non-Senior	31.03	24.44	6.58	148	1.03	6.36	<0.001**	8.63	4.54

Note: Est = Estimated; Obs = Observed; Diff = Difference; Round-off errors may apply; \*\* = Significant at 99%.

- ✓ Across all types of residential units, the ones studied here are more efficient than the national average. Study Y<sub>3</sub> LIHTC units indicate an EUI average that is 55% more efficient<sup>5</sup> than the National average and 43% more efficient than the Virginia average for multifamily rental housing.

**Figure 4.** Development average site EUI performance from May 2013 to April 2016 by project type.



### 3YR ENERGY DATA + TECH + BEHAVIOR

- ✓ Over 3 years, building technology and resident behavior continue to be strongly correlated. Regarding energy use and resident behavior, previous data analysis (Study Y<sub>1</sub>) provided quantifiable evidence supporting the hypothesis that “building technology and resident behaviors interact with each other and ultimately affect home energy consumption.” Study Y<sub>3</sub> data also indicate that building technology and resident behavior continue to be strongly correlated and significantly affect consumption.
- ✓ Over 3 years, fewer variables remain significant in reducing energy consumption. Study Y<sub>1</sub> provided quantifiable results that identified four direct correlates between resident behavior and energy use: temperature settings (winter/summer), use of a washer and dryer, and “education/training on building

<sup>5</sup> Energy Information Administration (EIA) 2009 Residential Energy Consumption Survey (RECS) Table CE1.4

systems and energy.” Study Y<sub>3</sub> data indicate a longer-term correlation between resident behavior and energy use for use of a washer and dryer, and “education/training on building systems and energy.”

- ✓ Over 3 years, resident interaction with technology contains a higher correlation with reduced energy consumption. Previous data analysis (Study Y<sub>1</sub>) provided quantifiable results that also identified two indirect correlates (increasing the interaction effect) between technology and behavior: temperature settings specifically during winter combined with knowledge about building systems. Study Y<sub>3</sub> data indicate five indirect correlates between technology and behavior.
- ✓ Over 3 years, as “temperature setting in thermostat during winter” stays at or below 68 degrees, there is a significant decrease in energy usage.
- ✓ Over 3 years, as “season when opening windows” occurs in summer and winter, there is a significant increase in energy usage. Over 3 years, as residents who report “humidity preference” move from low to medium levels it indicates a significant increase in energy usage.
- ✓ Over 3 years, as those who report “frequency of the use of dishwasher” move from low/medium use it indicates a significant increase in energy usage.
- ✓ Finally, data for units reporting “education/training on building systems and energy” indicate a significant decrease in energy usage.

### ***3YR ENERGY DATA + CLIMATE***

- ✓ Neither monthly energy use (not normalized) nor EUI (normalized) contained a significant effect due to climate variation across the sample. Study Y<sub>3</sub> data indicate a 3% effect due to climate, which is not a significant correlation (effect) with monthly energy use or energy footprint (EUI) within the sample population. This finding suggests that builder-developers working across the Commonwealth have lower risk of energy cost variability directly or indirectly impacting their developments.
- ✓ New construction units use more monthly energy and have a higher (EUI) than renovated units, similar to overall energy usage.
- ✓ Neither senior nor family units use more monthly energy and family units contain a higher EUI, similar to overall energy usage.
- ✓ Highly efficient housing design, construction and operation can minimize local climate variation effects which will increase energy demand in non-HPH. Findings support anecdotal evidence that recent high performance housing standards are normalizing the effect of local climate variation.

### 3YR ENERGY DATA + EDUCATION

- ✓ Research suggests that resident education on HPH technologies within their apartment/development is an opportunity for significant energy usage and cost savings. This work continues to find a significant correlation between residents with education on HPH technologies and reduced energy usage (resulting in cost savings and greater housing affordability) versus those without education.
- ✓ Residents with education had a lower average energy usage monthly and annually (over 3 years) by almost 15% (14.8%). Over 3 years, residents in units reporting “education/training on building systems and energy” contain a significantly lower monthly and annual energy usage versus those who report “no education/training on building systems and energy.”
- ✓ Residents with education had a lower energy bill by \$10.56 per month. Monthly energy use for residents reporting “education/training on building systems and energy” averaged 536 kWh over 3 years and cost \$60.95 per month.
- ✓ Residents without education had a higher energy bill. Based on savings for those with education, monthly energy use for residents reporting “no education/training on building systems and energy” averaged 628.9 kWh over 3 years and cost \$71.51 per month.
- ✓ Residents reporting education on HPH technologies saved \$126.72 per year on average. Annual energy use for residents reporting “education/training on building systems and energy” averaged lower than residents reporting “no education/training on building systems and energy” by 1,113.6 kWh over 3 years.

**Table 6:** Energy use and cost of energy for residents with and without education

	Energy Use (kWh)	Cost/kWh
W. Education	536.1	\$60.95
W/o. Education	628.9	\$71.51
Diff. (Monthly)	-92.8	-\$10.56
Diff. (Yearly)	-1,113.6	-\$126.72
Saving (%)	-14.8%	-\$14.8%

Note: costs calculated at price of \$0.1137/kWh, which was the VA state average for 2015.

### NON-GREEN AND GREEN DEVELOPMENT COSTS

- ✓ Data on construction costs of Virginia LIHTC projects built from 1998 – 2012 support previous research indicating that developer/builder organizations continue to adopt new technology and

adjust to associated costs. The difference in the total cost between green and non-green LIHTC developments, is not statistically different across the entire sample of development total costs.

- ✓ Data indicate a higher average total cost for non-green developments of 6.2% or \$7.15 per square foot (ft<sup>2</sup>) (see table 3).
- ✓ Data for LIHTC green developments indicate a lower average cost by 13% or \$10.08 per square foot in direct or “hard” costs and a higher average by 6.9% or \$2.93 per square foot in indirect and soft costs (see table 7).

**Table 7. Development costs: green versus non-green**

Average Cost Per ft <sup>2</sup>			
	Green	Non-Green	Diff. (± %)
Direct (Hard)	\$66.21	\$76.29	-13%
Indirect (Soft)	\$42.37	\$39.44	6.9%
Total	\$108.59	\$115.74	-6.2%

- ✓ As previously discussed, the sample would need higher resolution data to go beyond the ft<sup>2</sup> level of comparison in this study. Non-green LIHTC developments cost more per square foot but contained smaller total square foot sizing of units and developments since 2008, when green rating systems were integrated into Virginia LIHTC policy, contained a larger footprint.
- ✓ Since green developments occurred primarily after 2008, costs across the entire sample were analyzed in two ways: 1) *without* PPI inflation for non-green developments after 2008 and 2) *with* PPI inflation for non-green developments after 2008. *Without* PPI inflation for non-green developments, green developments cost more in 2013 dollars. *With* PPI inflation for non-green developments, green developments cost less in 2013 dollars. The resulting difference in cost per square foot between the non-green and the green developments was 6.9% less for green in 2013 dollars. However, none of these differences are statistically significant.
- ✓ Data indicate a higher average soft cost (see Table 8 and Figure 5) in the areas of:
  - professional services;
  - financing;
  - permits and fees;

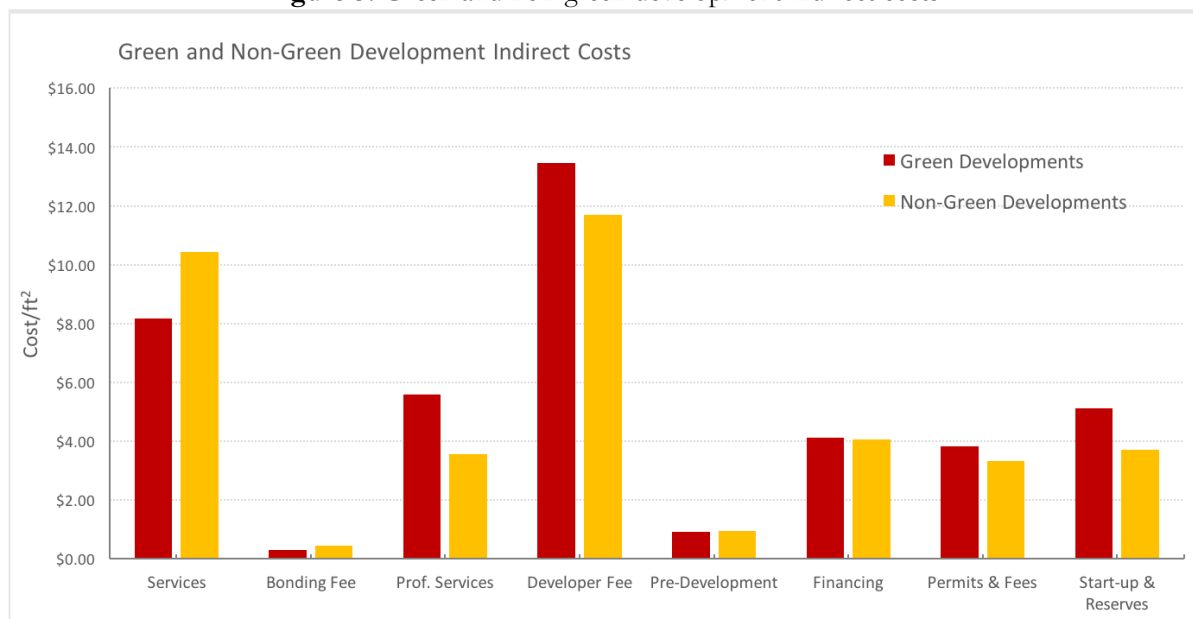
- developer fees; and
  - start-up and reserves.
- ✓ Data indicate a lower average soft cost in the areas of:
- services;
  - bonding fees; and
  - pre-development.
- ✓ Professional services include: Architect, Engineer, Real Estate Agents and Consultants, including Green Building Consultants (see Table 9). Financing refers to costs associated with financing the construction process, including: loan fee, loan interest, legal fees, real estate tax, insurance, bridge loan. Permits and fees are relative to the locality of the construction and refer to local government fees and permanent financing fees. Developer fees refer to allowed overhead costs for the builder-developer organization and start-up and reserves include marketing, rent-up, operating deficit, replacement reserve, furniture and equipment.
- ✓ Services contain general contractor services including overhead, profit and general requirements, bonding fees refer to costs associated with performance and bidding bonds and pre-development fees include market study, appraisal, environmental reports, tax credits.

**Table 8.** Detailed soft costs (\$/ft<sup>2</sup>): green versus non-green

Soft Cost	Green	Non-Green	Diff (± %)	Sig
Services	\$8.16	\$10.44	-21%	0.10
Bonding Fee	\$0.30	\$0.45	-33%	0.41
Prof. Services	\$5.59	\$3.57	36%	0.13
Pre-Development	\$0.93	\$0.96	-3%	0.95
Financing	\$4.12	\$4.07	1.2%	0.51
Permits & Fees	\$3.84	\$3.34	13%	0.38
Developer Fee	\$13.46	\$11.69	13%	0.45
Start-up & Reserves	\$5.13	\$3.72	27%	0.9

- ✓ These results suggest that across time and the entire set of developments sampled (green AND non-green), the average cost per square foot does not reflect a significant statistical difference. Therefore, neither non-green nor green developments deviate significantly enough from the overall average over time to indicate one set of the sample as having a higher cost per square foot. Therefore, over time, green development costs per square foot (especially the hard cost) have diffused into the industry at a similar level to non-green construction developments.

**Figure 5. Green and non-green development indirect costs.**



- ✓ Literature suggests that technology innovation diffusion must overcome developer-builder resistance for success (McCoy et al. 2012). The result of increased professional services and reduced general contracting (GC) services suggests that risk in this sample of LIHTC green developments is shared across multiple, key stakeholders in the project delivery process. Traditionally, and in the non-green sample, lower professional fees and higher general contracting (GC) services is indicative of risk being carried by the GC more than other stakeholders, which historically generates resistance to new technologies.
- ✓ A detailed analysis of the contribution of green building consultant fees to soft costs was undertaken in Table 9 below. These fees do not appear to be a primary contributor to higher soft costs in the green developments sampled.

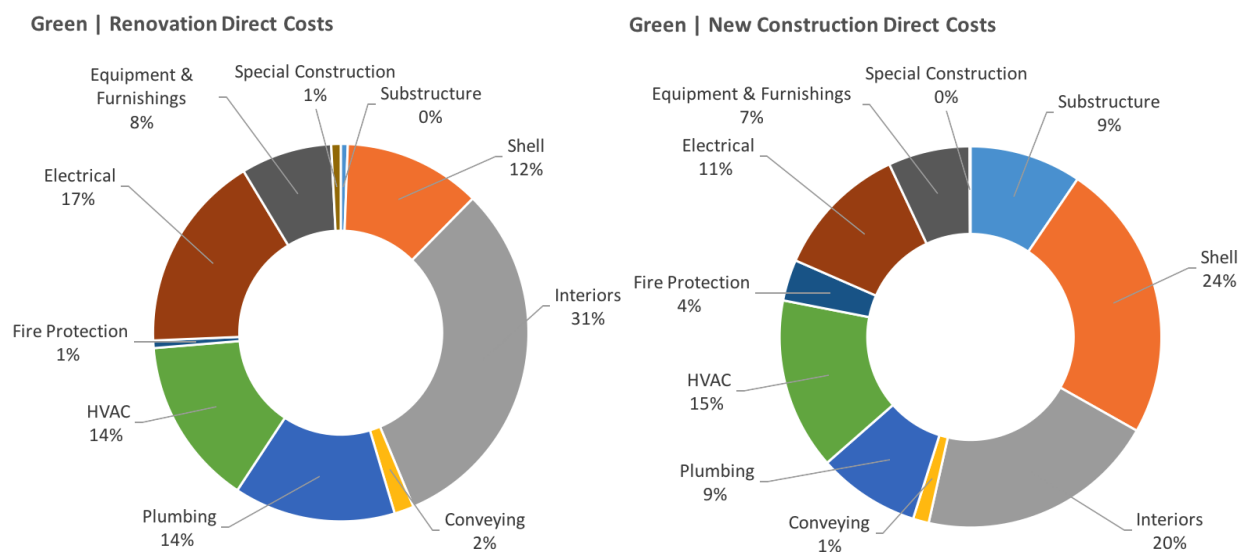
**Table 9.** Green building consultant fee overview

Unit of Analysis	Green Building Consultant Fee
Percentage of Total Cost	0.38%
Percentage of Indirect Cost	0.93%
Percentage of Professional Services (Indirect Cost)	16.34%
Fee \$/ft <sup>2</sup>	\$0.36
Fee \$/unit	\$ 336.66

### ***ENERGY USE AND DEVELOPMENT COSTS***

- ✓ Researchers sought to determine whether there was a positive relationship between green construction costs and energy saved by residents. Construction cost data of the green buildings were analyzed in the context of the magnitude of energy savings yielded by unit over 3 years (Y<sup>3</sup> study). Data modeling did not indicate a significant positive correlation between development costs and energy usage. While the design and construction process often requires a “bottom line” approach that could influence the likelihood of certain processes, technologies or products over others, our analysis does not indicate an influence.
- ✓ Green new construction and renovation development hard costs are driven by their scope of work (Figure 6). Virginia LIHTC Renovation projects do not typically remove interior drywall in the above grade walls, limiting their enclosure improvements (and costs) to airsealing, attic insulation and exterior continuous insulation. Instead renovation projects spend a higher percentage of their hard cost budgets on interiors and system retrofits, while new construction project hard costs are dominated by shell (enclosure) costs.

**Figure 6.** Green development (renovation and new construction) direct costs distribution.



## Conclusion

This report shares findings from a multi-year, mixed-methods study that measured the energy performance of Virginia’s green building multifamily housing stock. Over the last ten years, the Virginia Housing Development Authority (VHDA) has utilized green building rating system incentives as a policy vehicle in the Low-Income Housing Tax Credit (LIHTC) program to encourage energy efficiency (EE) in the affordable rental stock in Virginia (Climate Zone 4). The research addresses key issues related to EE and affordable housing through the measurement of actual, unit-level energy use in 237 apartments across 15 developments. Data are used to evaluate the effects of year to year operation, weather and behavior on energy use. Data, analysis and findings focus specifically on facilities constructed and certified to the EarthCraft Multifamily (ECMF) rating system in Virginia, one of the only datasets currently available that allows for this type of inquiry. As a second component of the study, development cost data were analyzed for 24 developments containing 1,351 apartments to compare the cost for building green versus non-green.

## The Role of Policy

The findings outlined in this report suggest VHDA’s green building incentives in the LIHTC program have been successful in promoting affordable housing development that saves residents on average, 45% on their

annual energy costs at little cost difference compared to standard housing. While the authors caution against overgeneralizing the findings beyond this study sample, lessons learned from balancing resident and builder-developer benefits through the use of incentive-based policy and performance-driven program design could contribute to the broader policy conversation currently aimed at reducing energy consumption in the built environment. Recent efforts to promote affordability and reduce energy consumption in Virginia's new and existing housing stock through model building codes and utility demand-side management programs could utilize this work to catalyze conversations regarding the the evaluation of energy-focused mandates and incentives, as well as prescriptive and performance-based policy design.

## Moving Forward | Closing the Gap

In 2016, VHDA's Board of Directors approved a change to the LIHTC program that could become a model for closing the energy efficiency information gap introduced earlier in this work. Beginning in 2017, builder-developers can improve their project competitiveness and maximize their green building QAP points by electing to achieve higher levels of certification under a 3rd party-rating system (EarthCraft and/or LEED) and committing to 2 years of benchmarking the performance of their development(s). The demonstrated energy savings afforded through the use of 3rd-party rating systems reduces uncertainty for affordable housing residents, while benchmarking aims to reduce information gaps, lags and risk when builder-developers invest in housing. Leveraging this data will enable stakeholders to make better decisions about the future development, design, construction and operation of affordable housing.

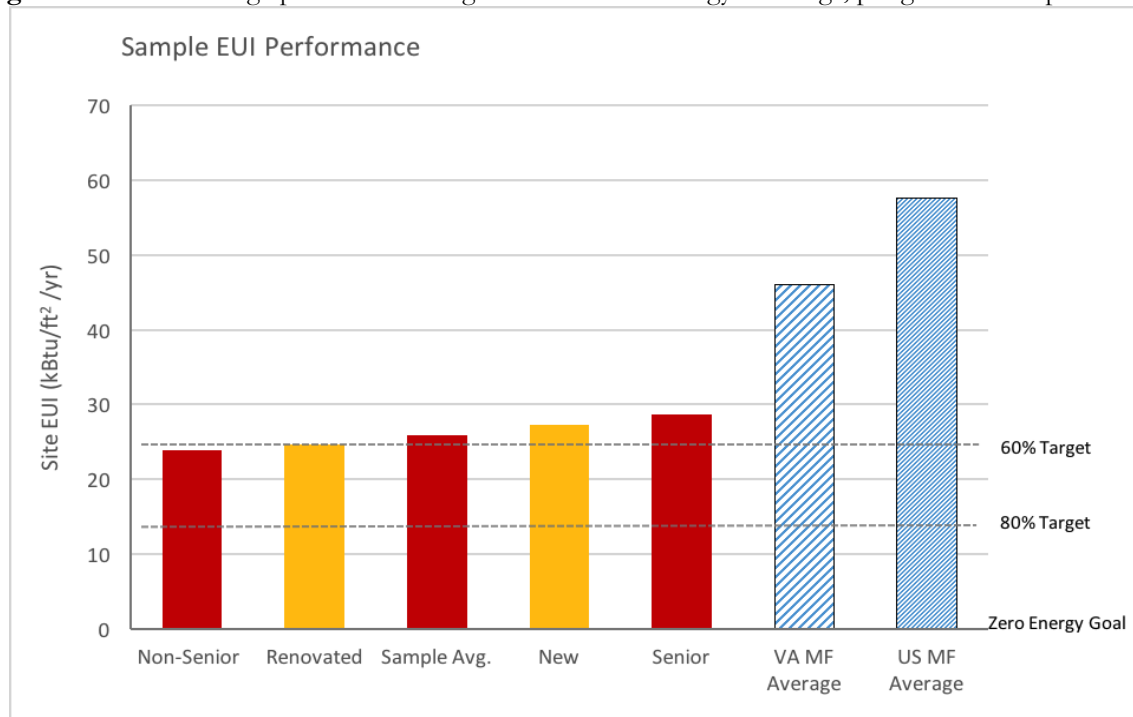
It is important to acknowledge the impact that housing evaluated in this study has on infrastructure and the environment. As utilities are faced with the challenge of providing reliable, affordable energy across an aging grid, energy efficient housing reduces peak load demand and stress on an aging infrastructure compared to standard housing. In the last two years, Virginia utilities have reported multiple peak load events<sup>6,7</sup> during the winter. These events are typically reserved during the height of the summer, late afternoon air conditioning season. Recent work by the Virginia Poverty Law Center (2017) reported that higher utility rates often contain the cost to build new power plants and meet demand. Focusing on energy efficiency programs and education provides a lower-cost alternative to adding infrastructure, while maintaining ageing infrastructure is still a major concern. Further development of energy efficient housing can yield benefits to utilities through reduced peak loads and greenhouse gas emissions. The AEC industry has set aggressive targets (Figure 7) for energy

<sup>6</sup> [http://www.richmond.com/business/article\\_12325e61-ccf1-533b-a631-14f9142b02b7.html](http://www.richmond.com/business/article_12325e61-ccf1-533b-a631-14f9142b02b7.html)

<sup>7</sup> [http://www.richmond.com/business/local/dominion-virginia-power-says-power-usage-broke-records-this-summer/article\\_d003b1ef-3298-5eea-a908-987b765c14f5.html](http://www.richmond.com/business/local/dominion-virginia-power-says-power-usage-broke-records-this-summer/article_d003b1ef-3298-5eea-a908-987b765c14f5.html)

and greenhouse gas emission reductions over the next ten years. The findings from this study suggest VHDA, LIHTC builder-developers and residents are ahead of non-LIHTC Virginia and national multifamily projects toward reaching these targets.

**Figure 7.** 2030 Challenge performance targets toward zero energy buildings, per green development type.



Finally, the trend of falling renewable energy prices, specifically the 60% decrease in solar photovoltaic systems over the last 5 years<sup>8</sup> is important to consider. Pairing the reduced risk and favorable economic conditions for energy efficient housing; renewable energy and other intelligent infrastructure technologies present an opportunity to re-envision best practices for utility metering structures in rental housing and public perceptions of affordable housing benefits to society.

## Limitations

It is important to recognize the limitations of this work. First, the data, analysis and findings focus specifically the energy use and construction costs of facilities constructed and certified to the EarthCraft Multifamily (ECMF) rating system in Virginia, one of the only datasets currently available that allows for this type of

<sup>8</sup> NREL U.S. Solar Photovoltaic System Cost Benchmark <http://www.nrel.gov/docs/fy16osti/66532.pdf>

inquiry. Other potential benefits of 3rd party verified, green rating systems were beyond the scope of this project. The energy use analysis focuses on electric use only and energy costs in terms of \$/kWh. The analysis excludes utility taxes, tariffs and services fees since the variability in utility fee and municipal tax structures across the state distorts the energy use analysis. The cost data analysis compares non-green and EarthCraft certified-level LIHTC developments that were built spanning a 14 year period. The authors used the PPI to normalize the costs to reduce the impact of the inflation and technology factors since data for more recently constructed non-green LIHTC developments in Virginia was not available due to the majority of builder-developers have elected to pursue a green building certification over the last ten years. Since 2012, developers participating in VHDA's LIHTC program could elect to pursue higher levels of EarthCraft certification (example Gold or Platinum). This work does not consider the impact of developments pursuing higher levels of performance in the context of energy use, cost and/or educational intervention impacts due to the timing of the study and data availability.

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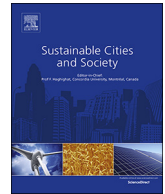
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# Time effects of green buildings on energy use for low-income households: A longitudinal study in the United States

Dong Zhao<sup>a,b,\*</sup>, Andrew P. McCoy<sup>c</sup>, Philip Agee<sup>c</sup>, Yunjeong Mo<sup>a</sup>, Georg Reichard<sup>c</sup>, Freddy Paige<sup>d</sup>

<sup>a</sup> School of Planning, Design, and Construction, Michigan State University, East Lansing, MI, 48824, United States

<sup>b</sup> Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI, 48824, United States

<sup>c</sup> Myers-Lawson School of Construction, Virginia Tech, Blacksburg, VA, 24061, United States

<sup>d</sup> Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg, VA, 24061, United States

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## ABSTRACT

The U.S. government has included green building policy in affordable housing programs for years. However, little to no evidence is available to elucidate this policy's efficacy in the context of energy performance and financial savings. This paper reports a longitudinal study that investigates time effects of such policy on the energy performance in low-income housing units. The researchers collected monthly energy use data over three years from 310 residential units and conducted profile analysis and MANOVA. Results indicate that (1) green buildings' energy performance is consistent across years; (2) construction type, technology level, and apartment size significantly and consistently affect energy use; and (3) occupant type inconsistently affects energy use. Results suggest financial savings of \$648 per year due to reduced energy usage in green buildings. The savings equate to 9.3%, 5.6%, and 3.5% of annual income for extremely low-income, very low-income, and low-income families, respectively. Savings represent a 26.6%–37.5% reduction of energy expenditure for low-income households. Findings strongly suggest that green building incentives and the diffusion of green building practice is resulting in affordable housing systems.

## 1. Introduction

Affordable housing has long been a national effort in the United States. In the early decades of the implementation of the Housing Act of 1937 (Mo, Zhao, McCoy, Du, & Agee, 2017; Vale, 2007), the federal government's involvement was directly funding affordable housing development including construction costs; while state and local public housing authorities (PHA) covered the operational and maintenance costs. In return, PHAs owned the properties and controlled the design, construction, and tenant selection. Beginning in the 1960s, the U.S. Department of Housing and Urban Development (HUD) started to prioritize public-private partnerships that encouraged private developers to develop affordable housing by offering subsidies and vouchers to offset development and construction costs. To date, the Low Income Housing Tax Credit (LIHTC) program has become the largest and most significant federal program for the production and preservation of affordable housing for low-income families in the nation (Collinson, Ellen, & Ludwig, 2015). Eligible LIHTC-assisted projects require that 20% or greater of residents have incomes below 50% of the area median income (AMI) and 40% or greater of residents have incomes below 60% of AMI. The federal government annually earmarks \$6

billion to the LIHTC program which has supported more than 2 million residential units and retained a large tax credit portfolio (Khadduri, Climaco, Burnett, Gould, & Elving, 2012).

Over the same 40–50 years, building energy use reduction has also been a national effort. In the U.S. residential buildings account for at least 21% of energy consumption and carbon emissions based on the U.S. EIA (2016). This usage represents 20 quadrillion British thermal units (BTU) and US\$218 billion in energy expenditure. Many low-income families are involved in energy poverty since they must allocate significantly more of their household income to energy expenditures than other households (Bird & Hernandez, 2012). Low-income households often live in homes that are not energy efficient and they are unable to afford energy-saving measures (Guerra Santin, 2011; Langevin, Gurian, & Wen, 2013). The broad concept of green building can be defined as aspects of energy efficiency, sustainability, and environmentally friendly products (Adomatis, 2012; Hodges, 2005; Tucker, Pearce, Bruce, McCoy, & Mills, 2012). In this research, the authors focus on human-centered energy efficiency to measure the performance of green building (McCoy, Zhao, Ladipo, Agee, & Mo, 2018). The focus on energy performance is consistent with LIHTC policy.

\* Corresponding author at: 552 W Circle Drive, East Lansing, MI 48824, United States.  
E-mail address: [dzhao@msu.edu](mailto:dzhao@msu.edu) (D. Zhao).

To improve building energy efficiency, the architecture, engineering, and construction (AEC) industry has engaged in R&D for building technologies. These technologies range from enclosure systems advancements (e.g. spray-applied insulation and weather resistant barriers, air sealing techniques, and high-performance glazing systems) to sub-system advancements (e.g. inverter-driven heat pumps, efficient lighting and appliances, and low-flow water fixtures). Green buildings also provide a healthier built environment, addressing indoor environmental quality (IEQ) and occupant quality of life (Amiri, Mottahedi, & Asadi, 2015; Baughman & Arens, 1996; Hoskins, 2003; Singh, Syal, Grady, & Korkmaz, 2010; Singh, Syal, Korkmaz, & Grady, 2010; Spengler & Sexton, 1983). The U.S. Department of Energy (DOE) has set long-term goals toward 50% energy reduction in buildings and committed to catalyzing green buildings at a national level through model building codes and supporting third-party green rating systems (e.g. LEED, Energy Star, and EarthCraft).

As a part of this national effort, HUD and local housing finance agencies (HFAs) have integrated green building rating systems into state-led LIHTC programs. Financial support from the LIHTC programs address essential barriers to green building implementation, including higher initial costs of design and construction (Beheiry, Chong, & Haas, 2006; Lee, Chin, & Marden, 1995; Zhao, McCoy, & Smoke, 2015). At the federal level, the LIHTC program does not mandate green building rating programs for apartment development; however, the U.S. Internal Revenue Service (IRS) specifies that energy efficiency shall be considered in state-level requirements for LIHTC development. In practice, HFAs provide financing for affordable housing and are the agencies that award the IRS credits. The IRS credits are distributed to developers based on the Qualified Allocation Plan (QAP).

To date, all state PHAs have incorporated some form of green building policy (e.g. discrete green building measures and/or green building rating systems) into their QAPs. As listed in Table 1, the QAP either requires LIHTC applicants (e.g., the developer or builder) to participate in a green building rating system or encourages them to achieve green building certification by offering additional scoring points.

LIHTC is an ideal platform to gauge home energy efficiency; however, little to no research has fully utilized this platform to investigate green homes' energy performance and economic impact. This knowledge gap prevents policymakers from a better understanding of green building efficacy, particularly for low-income households. To address part of this gap, as shown in Fig. 1, this study has two objectives: (1) to identify energy performance of LIHTC-assisted green buildings over time, and (2) to determine economic impacts on low-income households as a result of these green buildings. In reaching the objectives, the authors have conducted a longitudinal study on energy consumption of LIHTC-assisted green buildings over 36 consecutive months from 2013 to 2016. Unlike cross-sectional studies that only reveal static homogeneity and heterogeneity, longitudinal study uncovers dynamic trends

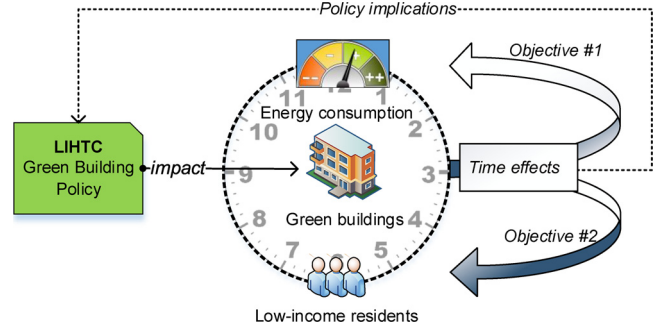


Fig. 1. Diagram of research design and objectives.

of energy use and time effects of energy efficiency (Diggle, 2002). In other words, this study focuses on whether or not energy performance is stable, durable, and consistent over time in these green buildings. Energy use trends and time effects unveiled from this study contribute to the robust long-term decision-making for both energy and housing policymakers. In this regard, the authors also discuss data-driven policy implications based on analytical results.

## 2. Materials and methods

### 2.1. Data

Fig. 2 displays the 310 residential units across 16 developments in the state of Virginia from which energy use data were collected. Apartment-level electricity data were collected on a monthly basis from May 2013 to April 2016 using an online benchmarking software. The authors applied a method of geographic cluster sampling (or termed area cluster sampling). The cluster sampling technique has been widely used in research by many statistic agencies including the World Bank (Himelein, Eckman, & Murray, 2013) and U.S. Department of Agriculture (2016). In this research, the geographic clusters are based on the metropolitan statistical area (MSA), a geographical region with a relatively high population density at its core and close economic ties throughout the area (U.S. Census Bureau, 2016). MSA is a result of national standards for statistical purposes and has been adopted by many federal agencies including the Census Bureau and HUD. The sampling strategy aligns with the referenced national standards and, therefore, allows for representing a larger population in each statistical area and producing more accurate analytical results (Himelein et al., 2013). To minimize the disturbance from missing data (Everitt, 1998; Molenberghs & Verbeke, 2000), the study used longitudinal data with complete records during the whole 3-year period.

Virginia is selected for data collection because it contains a large number of LIHTC-assisted green apartments with considerable quality. Since 2007, the Virginia Housing Development Authority has integrated

**Table 1**  
Summary of state-level LIHTC green building programs in the United States.

Certification	Require Certification by State	Encourage by State
<ul style="list-style-type: none"> <li>• LEED for Homes</li> <li>• Home Energy Rating System</li> <li>• EarthCraft House</li> <li>• Enterprise Green Communities Criteria</li> <li>• National Green Building Standard</li> <li>• ENERGY STAR appliances</li> <li>• Green Point Rated Multifamily Guidelines</li> <li>• Green Globes</li> <li>• LEED for Neighborhood Development</li> </ul>	Alaska, Arkansas, Arizona, California, Colorado, Connecticut, District of Columbia, Delaware, Florida, Georgia, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Nebraska, North Carolina, Louisiana, Massachusetts, Maryland, Michigan, Minnesota, Missouri, Mississippi, Montana, New Hampshire, New Jersey, Nevada, New York, Ohio, Oklahoma, Oregon, Rhode Island, South Dakota, Tennessee, Texas, Utah, Virginia, Washington	Hawaii, North Dakota, New Mexico, Pennsylvania, South Carolina, Vermont, Wisconsin, West Virginia, Wyoming

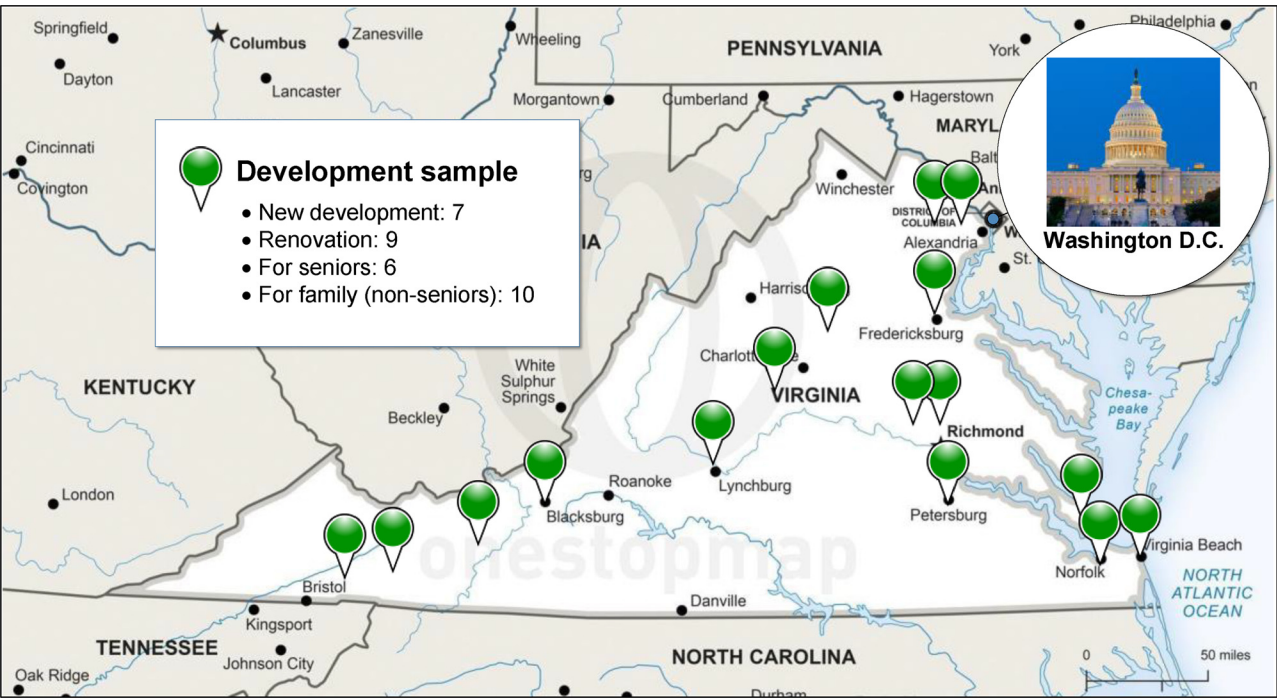


Fig. 2. Geographical display of sampled residential developments.

Table 2  
Longitudinal analysis periods.

Time Separation	Period	Month	Duration	Dominant Seasonal Load
Annual	Y <sub>1</sub>	May 2013–Apr. 2014	12 months	Cooling/heating
	Y <sub>2</sub>	May 2014–Apr. 2015	12 months	Cooling/heating
	Y <sub>3</sub>	May 2015–Apr. 2016	12 months	Cooling/heating
Semiannual	T <sub>1</sub>	May 2013–Oct. 2013	6 months	Cooling
	T <sub>2</sub>	Nov. 2013–Apr. 2014	6 months	Heating
	T <sub>3</sub>	May 2014–Oct. 2014	6 months	Cooling
	T <sub>4</sub>	Nov. 2014–Apr. 2015	6 months	Heating
	T <sub>5</sub>	May 2015–Oct. 2015	6 months	Cooling
	T <sub>6</sub>	Nov. 2015–Apr. 2016	6 months	Heating

green building rating systems as an incentive for the state QAP (McCoy et al., 2018). Virginia ranks in the top 10 in the nation and the first in the southeastern region on recent LIHTC production: building more than 2000 residential units per year. All of the sample developments were built or renovated after 2009, making current green building technologies available in the design and construction. Further, all buildings sampled for this research were certified by the EarthCraft green building rating system. The authors acknowledge that there are other green building rating systems (e.g. LEED, Enterprise Green Communities) available to policymakers and developers. The analysis represented in this paper focuses only on EarthCraft certified developments in Virginia because (1) the EarthCraft program in Virginia’s QAP represents the only accessible database with the detailed technical information of design and construction available for this type of analysis and (2) 100% of the Virginia LIHTC project since 2007 elected to pursue EarthCraft certification.

Data for energy analysis included monthly electricity use (kWh), construction type (i.e., new or renovated), occupant type (i.e., family or senior), technology level, climate, and conditioned floor area data. Residential units were 100% electric in fuel source. Monthly electricity use was sourced with residents’ consent and with help from property managers. In 2013, the authors invited residents to an onsite educational meeting in the form of a “pizza party” at every development. As part of the meeting, the study goals were introduced to residents, the

energy efficiency of apartments where they lived, and energy efficiency technologies placed within the apartments. The research team provided a \$25 gift certificate (financial incentive) to participants who filled out a utility release form, a behavior survey, and agreed to provide access to their unit’s electricity utility account. Meanwhile, the authors partnered with developers and property managers to collect data from the development’s green building certification. Particularly, the certification provides housing unit design specifications and a Housing Energy Rating Certificate (HERC) document to measure the level of green building technology and simulated energy performance (Zhao, McCoy, & Du, 2016). The HERC is based on a score (termed HERS) that is a nationally recognized asset scoring system in the U.S., of which 100 indicates an apartment built to current model code standards and lower scores indicate higher energy efficiency. Other data for economic impact analysis (e.g., local AMI values and electricity prices) were derived from national census databases: the 2012–2016 American Community Survey (ACS) and American Housing Survey (AHS).

Table 2 summarizes time separation and periods on an annual or semiannual basis. For the annual-based separation, the authors aggregated monthly energy data into 3 periods (i.e., Y<sub>1</sub>, Y<sub>2</sub>, and Y<sub>3</sub>) with a duration of 12 months for each period. This time scale demonstrates electricity use trends across the first, second, and third year. For the semiannual-based separation, the authors aggregated energy data into 6 periods (i.e., T<sub>1</sub>, T<sub>2</sub>, ..., T<sub>6</sub>) with a duration of 6 months for each period.

Measurements at this time scale avoid bias due to discrepancies of energy use between heating and cooling-intensive seasons. For example, annual energy use may not change when a home has higher consumption for cooling and lower consumption for heating. Virginia's heating season (climate zone 4A), often starts in November and ends in April. Therefore, the two sets of time separation allowed this longitudinal study to analyze yearly and seasonal time effects.

## 2.2. Methods

Through longitudinal study, the authors performed three analytical analyses: (1) profile analysis, (2) multivariate analysis of variance (MANOVA) and (3) economic impact analysis. The authors separated the 3-year duration into 12-month and 6-month periods to track longitudinal trends and utilized SAS v12 software for all analysis.

Profile analysis is a sequence comparison method that identifies patterns between cohorts across time points. Mathematically, it is the multivariate equivalent of repeated measures. Profile analysis can visualize patterns through graphs of data (e.g., plots and curves) and thus is more informative when comparing the same dependent variables between cohorts over multiple time points (Srivastava, 1987). Typical to profile analysis, this work tested the pattern's parallelism, level, and flatness. The parallelism test seeks whether or not profiles have the same trend across time points, which is reflected in the curve's shape or slope change. The level test checks if profiles have equal levels on average (i.e., average energy use) across time points. The flatness test identifies a profile's time effect assuming its curve's slope is 0. As a supplement, matched-pairs *t*-tests were performed to confirm the observed patterns.

The authors used profile analysis to visualize cohort effects of energy use across three years. Specifically, two sorts of cohort effects were analyzed. One cohort sort is based on construction type and has two cohorts: newly constructed buildings (hereafter termed New) and renovated buildings (hereafter termed Renovation). The other cohort sort is based on occupant type and has two cohorts: units designed for senior residents (hereafter termed Senior) and non-senior family residents (hereafter termed Family). Based on HUD regulations (2013), senior housing refers to facilities and communities for persons age 55 and older. All cohorts under study were fixed and thus changes in time were not confounded by cohort differences (Fitzmaurice, Davidian, Verbeke, & Molenberghs, 2008). Therefore, results from profile analysis enabled researchers to delineate the differences of energy use trends between New and Renovation and between Senior and Family apartments and occupants.

MANOVA analysis simultaneously analyzes the responses of many correlated dependent variables. We use MANOVA to explore how various factors affect energy use and whether or not such effects change over time. Specifically, the between-subject effect and within-subject effect over time were tested (Fitzmaurice et al., 2008; West, Galecki, & Welch, 2014). The between-subject effect represents a factor's effect across all building units, and the within-subjects effect represents a factor's repeated effect over time. Mathematically, the between-subject effect was modeled by fitting the sum of the repeated measures to the model effect; and the within-subject effect was modeled with a function that fits differences in the repeated measures. In this study, the profile function was employed to perform MANOVA on energy data over time  $Y_1$ – $Y_3$ , and the compound function was employed on data over time  $T_1$ – $T_6$  (Scheiner & Gurevitch, 2001).

The MANOVA analysis considers five specific effects (i.e., construction type, occupant type, building technology level, climate, and conditioned floor area). Eq. (1) expresses the multivariate regression formula that models these effects. The five effects correspond to five critical factors that directly and significantly affect home energy consumption, which the literature refers to as: building, user, operation systems, climate, and space (Anderson et al., 2017; Yu, Fung, Haghighat, Yoshino, & Morofsky, 2011). In addition, the number of

occupants were very similar across the sample and thus not included in the analysis. The factor of climate is represented using the 10-year average ratio of heating degree days (HDD) and cooling degree days (CDD). The research team sourced HDD/CDD data from the U.S. NOAA (2016) database. Other factor data were sourced from HERC documents during data collection.

$$E_{it} = \begin{bmatrix} E_{i1} \\ E_{i2} \\ \vdots \\ E_{iT} \end{bmatrix} = \beta_0 + \beta_1 CT + \beta_2 OT + \beta_3 BT + \beta_4 WT + \beta_5 HS + \varepsilon_{it}, \quad \forall t = 1, 2, \dots, T \quad (1)$$

where:

$E_{it}$  = the electricity use at the *i*th residential unit during time period *t*;

$CT$  = the effect for construction type (i.e., New versus Renovation);

$OT$  = the effect for occupant type (i.e., Senior versus Family);

$BT$  = the effect for building technology level (i.e., HERS score);

$WT$  = the effect of weather (i.e., the ratio of HDD/CDD);

$HS$  = the effect for apartment size (i.e., the conditioned floor area).

Economic impact analysis is used to identify financial benefits from energy savings. Energy savings were calculated by comparing observed energy use for the sample to Virginia statewide average energy use. To provide a holistic view, the researchers compared the energy savings to the average of Virginia low-income households and to the average of all Virginia households (U.S. EIA, 2016). The financial benefit is represented in monetary value *V* with a rate of income *R*. The team then converted benefits and prices into a 2014 dollar value (\$) to mitigate for inflation influence. *V* and *R* are measured using the following Eqs. (2) and (3), respectively.

$$V = (E_0 \times P_0) - \frac{\sum_{i=1}^n \sum_{j=1}^{12} (E_{ij} \times P_{ij})}{n} \quad (2)$$

$$R = \frac{V \times n}{\sum_{i=1}^n I_i} \quad (3)$$

where:

*V* = the annual financial benefit value (in \$);

*R* = the annual financial benefit rate (in %);

$E_{ij}$  = the observed annual energy use in the *i*th residential unit in month *j* (in kWh);

$E_0$  = the average residential energy use (in kWh);

$P_{ij}$  = the local utility price for the *i*th residential unit in month *j* (in \$/kWh);

$P_0$  = the average utility price (in \$/kWh); and

$I_i$  = the local low-income threshold (in \$).

## 3. Results

### 3.1. Descriptive analysis

Table 3 summarizes electricity use over time, based on annual and semiannual delineations. 3-year overall electricity use is 533 kWh per month and its standard deviation is 269. Electricity uses during  $Y_1$ ,  $Y_2$ , and  $Y_3$  were 514, 558, and 525 kWh, respectively, close to the 3-year overall use. The energy usage for the observed period was tested against climate factor (i.e., HDD and CDD) and no significant difference of energy usage was found across the three years  $Y_1$ ,  $Y_2$ , and  $Y_3$  ( $F = 1.72$ ,  $p = 0.18$ ). Results indicate high-performance buildings' stable and consistent energy performance across three years. Semi-annual electricity uses over  $T_1$ ,  $T_3$ , and  $T_5$  were 419.32, 466.54, and 471.33 kWh, respectively. Semi-annual electricity use is lower than the 3-year overall electricity use and each is significantly different from each other statistically ( $F = 5.04$ ,  $p < 0.01$ ). Similarly, electricity uses during  $T_2$ ,  $T_4$ , and  $T_6$  were 640.30, 664.53, and 577.30 kWh, respectively. Each time

**Table 3**  
Summary of energy use over time (kWh/month).

Separation	Period	Mean	Std. Dev.	Lower CL	Upper CL	Min.	Max.
Overall	3-year	532.66	268.66	523.92	553.30	40.00	1906.33
Annual	Y <sub>1</sub>	514.38	206.53	483.11	545.65	60.58	1704.67
	Y <sub>2</sub>	558.46	233.05	523.18	593.75	48.76	1721.22
	Y <sub>3</sub>	525.17	244.16	488.20	562.13	64.00	1608.42
Semiannual	T <sub>1</sub>	397.89	198.68	386.20	452.45	70.00	1503.00
	T <sub>2</sub>	630.86	247.27	607.82	672.78	51.17	1906.33
	T <sub>3</sub>	457.55	230.98	434.60	498.47	57.49	1660.84
	T <sub>4</sub>	659.32	276.76	630.63	698.42	40.00	1781.67
	T <sub>5</sub>	471.66	249.74	436.35	506.31	56.33	1668.00
	T <sub>6</sub>	578.67	269.74	540.45	614.39	71.67	1756.67

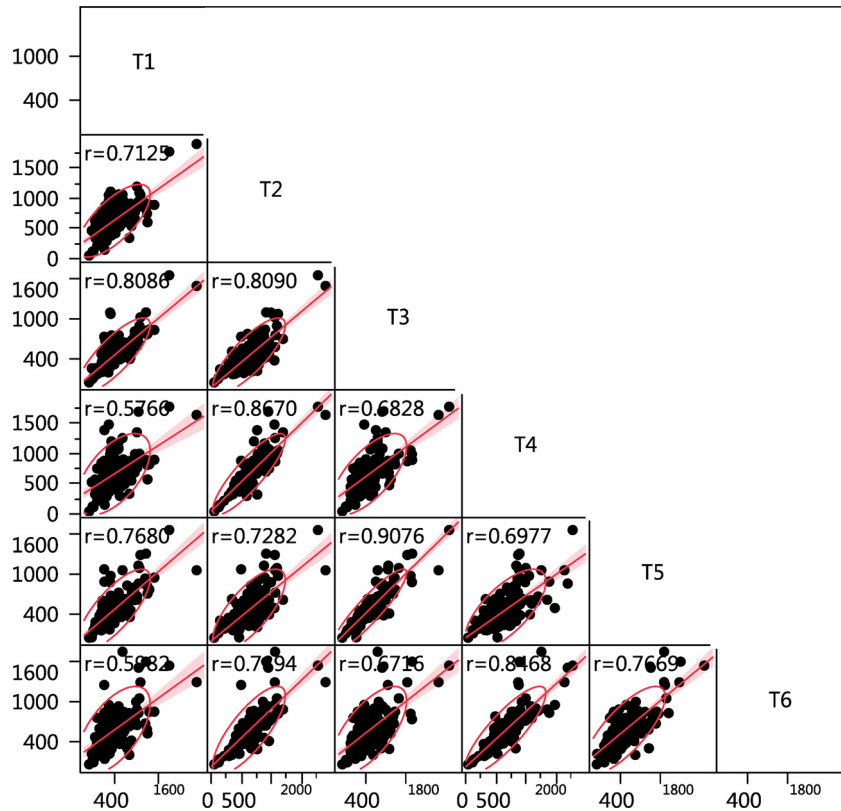


Fig. 3. Scatter plots of energy use over time showing correlations.

period was slightly higher than the 3-year overall use and significantly different statistically as well ( $F = 4.05, p = 0.02$ ). The differences indicate that units use more energy in heating seasons than cooling seasons and results confirm that electricity use fluctuates by season. In the next section, the correlation analysis explores these fluctuations.

Fig. 3 displays an array of scatter plots showing the correlation of electricity use across seasons. The plots show that electricity uses during T<sub>1</sub>, T<sub>3</sub>, and T<sub>5</sub> were closely correlated, and electricity uses during T<sub>2</sub>, T<sub>4</sub>, and T<sub>6</sub> were closely correlated. For example, the correlation between T<sub>1</sub> and T<sub>3</sub> was stronger than between T<sub>1</sub> and T<sub>2</sub>. Specifically, the highest correlation of electricity use ( $r = 0.908$ ) occurred between T<sub>3</sub> and T<sub>5</sub>, indicating a strong linear association. Results confirm previously-identified fluctuations and quantify the trend. Scatter plots also indicate a slight decrease in correlation due to increasing durations between the observation periods. For electricity use one year apart (i.e., across two time periods), the correlation between T<sub>1</sub> and T<sub>4</sub> ( $r = 0.577$ , longer duration) was weaker than that between T<sub>1</sub> and T<sub>2</sub> ( $r = 0.712$ , shorter duration); or the correlation between T<sub>2</sub> and T<sub>5</sub> ( $r = 0.728$ , longer duration) was weaker than that between T<sub>2</sub> and T<sub>3</sub>

( $r = 0.809$ , shorter duration). The resulting variability suggests the effect of external factors on electricity use, such as weather or occupant behavior across years. In addition, most off-diagonal values in the plots were lower than 0.9, indicating little multicollinearity and therefore a stable model for MANOVA. In other words, the predictive power and reliability of the model as a whole were satisfied (Hill & Lewicki, 2006).

3.2. Profile analysis

Fig. 4 illustrates the profile analysis results showing the cohort effects of energy use on an annual basis. In Fig. 4a, the profile analysis results are separated by construction type and present parallelism, level effects, and an absence of flatness. Parallelism indicates differences by type (comparing slopes), level effects indicate differences by electricity use (y-axis), and flatness (or absence thereof) indicates differences (up or down) over time (x-axis).

The two slopes are nearly parallel, indicating similar electricity use patterns between New and Renovated apartments. The slope of the new (mean = 576.57 kWh) units are uniformly higher than of the

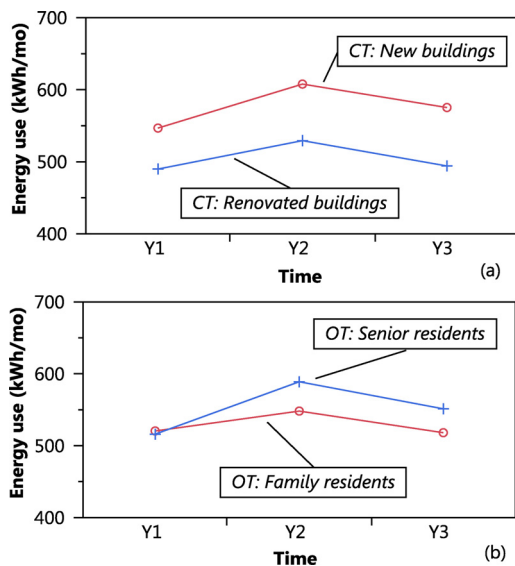


Fig. 4. Energy use trends across Y<sub>1</sub>–Y<sub>3</sub> by (a) construction type and (b) occupant type.

Renovated (mean = 504.42 kWh) units, indicating a consistent level difference. The difference of 72.15 kWh is statistically significant confirmed by the matched pairs *t*-test ( $t = 9.39$ ,  $p = 0.01$ ). The slopes indicate an absence of flatness (i.e., slope  $\neq 0$ ) or a change in energy use over time. Therefore, combined results suggest that the Renovated units sampled used 12.5% less electricity than the New units. In Fig. 4b, the profile analysis delineates absence of parallelism, level effects, and flatness by occupant type. The two slopes diverge, indicating different energy use patterns between Senior and Family occupants. The slopes' level effects become moot due to a lack of parallelism. The matched pairs *t*-test confirms no significant level difference ( $t = 1.66$ ,  $p = 0.24$ ) statistically across the sample by occupant type. The slopes are not flat (i.e., slope  $\neq 0$ ), indicating an effect of time on energy use. Therefore, results suggest that Senior occupants may not have consistently used more energy than Family occupants (i.e., non-seniors) in the sample. For example, seniors typically prefer higher set points, which leads to more consumption during heating but less during cooling – thus canceling each other out over a full year. The further analysis below separates for the heating and cooling periods T<sub>1</sub>–T<sub>6</sub> to test this idea of seasonal changes.

Similarly, Fig. 5 illustrates the results of profile analysis showing cohort effects of electricity use on a semi-annual base. The profile slopes

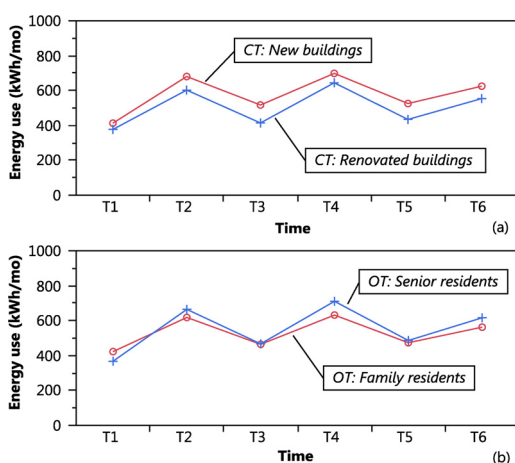


Fig. 5. Energy use trends across T<sub>1</sub>–T<sub>6</sub> by (a) construction type and (b) occupant type.

indicate a pattern of fluctuation. In Fig. 5a, the profile analysis by construction type depicts parallelism, level effect, and an absence of flatness. The two slopes are nearly parallel, indicating similar energy use patterns between New and Renovated units. The slope of the New unit sample is consistently higher than that of the Renovation unit sample, indicating a consistent level difference. The difference is also statistically significant based on the matched pairs *t*-test ( $t = 7.23$ ,  $p < 0.01$ ). The slopes show no flatness (i.e., slope  $\neq 0$ ), indicating a change in energy use over time. Therefore, results confirm previously identified consistent electricity use differences between new and renovated housing units. Fig. 5b indicates an absence of all three, though: parallelism, level effect, and flatness. Similar to Fig. 4b, the energy use slopes intertwine with each other early, indicating different energy use patterns between family and senior residents. The slopes are nearly overlapping, indicating a moot level difference. The matched pairs *t*-test identifies the level difference is not statistically significant ( $t = 1.20$ ,  $p = 0.24$ ). The slopes are not flat (i.e., slope  $\neq 0$ ), indicating an effect of time on energy use. Additional matched pairs *t*-tests on energy use indicate no statistically significant difference ( $t = -0.63$ ,  $p = 0.60$ ) for cooling-intensive periods (T<sub>1</sub>, T<sub>3</sub>, and T<sub>5</sub>) but a statistically significant difference of 59.61 kWh ( $t = 6.02$ ,  $p = 0.03$ ) for heating-intensive periods (T<sub>2</sub>, T<sub>4</sub>, and T<sub>6</sub>). These results strongly suggest that the senior residents used 9.9% more electricity for heating than family residents (i.e., non-seniors). Such a finding is noteworthy and needs to be fully considered by architects, engineers, builders, and energy raters for the design and construction of units.

### 3.3. MANOVA analysis

Table 4 shows results of the MANOVA analysis of energy use across Y<sub>1</sub>–Y<sub>3</sub>. The between-subjects effects from CT, BT, and HS are statistically significant while that from OT and WT are not significant. The results are consistent with the literature, indicating that the construction type ( $F = 4.3$ ,  $p = 0.04$ ), building technology ( $F = 10.67$ ,  $p = 0.01$ ), and floor area ( $F = 41.55$ ,  $p = 0.01$ ) significantly affect electricity use. The results show that the two occupant types in this sample are not a significant factor, indicating that electricity use is stable regardless of senior residents or families and similar to the parallelism, level effect, and flatness findings. Unlike literature that asserts weather as an impact factor on energy use, the results do not produce a similar observation and we speculate the difference as a result of the sample's close geographic distance: because the sampled units were located in the same state and climate zone, the effect of weather was minimal. Moreover, the within-subject effect from WT is statistically significant ( $F = 4.05$ ,  $p = 0.02$ ) and that from CT, OT, BT, and HS are not significant. This finding indicates weather effect changes across Y<sub>1</sub>, Y<sub>2</sub>, and Y<sub>3</sub> while other effects do not. In other words, except the weather, no interaction effect between time and other factors were found. It is noteworthy that

Table 4  
MANOVA results of energy use across Y<sub>1</sub>–Y<sub>3</sub>.

Statistic	Value	<i>F</i>	Num. df	Den. df	<i>p</i>
<b>Between-subjects</b>					
CT	0.027*	4.37	1	164	0.04
OT	0.002	0.39	1	164	0.53
BT	0.065**	10.69	1	164	< 0.01
WT	0.013	2.06	1	164	0.15
HS	0.253**	41.55	1	164	< 0.01
<b>Within-subject</b>					
Time (Year)	0.033	2.65	2	163	0.07
CT × Year	0.010	0.81	2	163	0.45
OT × Year	0.036	2.95	2	163	0.06
BT × Year	0.015	1.24	2	163	0.29
WT × Year	0.050*	4.05	2	163	0.02
HS × Year	0.009	0.69	2	163	0.50

Note: \* = significant at 95%, \*\* = significant at 99%.

**Table 5**  
MANOVA results of energy use across T<sub>1</sub>–T<sub>6</sub>.

Statistic	Value	F	Num. df	Den. df	p
<b>Between-subjects</b>					
CT	0.027*	4.37	1	164	0.04
OT	0.002	0.39	1	164	0.53
BT	0.065**	10.69	1	164	< 0.01
WT	0.013	2.06	1	164	0.15
HS	0.253**	41.55	1	164	< 0.01
<b>Within-subject</b>					
CT × Year	0.010	0.81	2	163	0.45
OT × Year	0.036	2.95	2	163	0.06
BT × Year	0.015	1.24	2	163	0.29
WT × Year	0.050*	4.05	2	163	0.02
HS × Year	0.008	0.69	2	163	0.50
CT × Season	0.001	0.11	1	164	0.75
OT × Season	0.037*	6.03	1	164	0.02
BT × Season	0.017	2.83	1	164	0.09
WT × Season	0.044**	7.24	1	164	0.01
HS × Season	0.004	0.72	1	164	0.40

Note: \* = significant at 95%, \*\* = significant at 99%.

the effect of Time (year) is not statistically significant, indicating a consistent energy use trend across three years. Findings suggest that the effects of construction, occupant, technology level, and apartment size are consistent over years and do not contain more of one effect during one time period.

Table 5 shows results of the MANOVA analysis of energy use across T<sub>1</sub>–T<sub>6</sub>. The between-subjects effects from CT, BT, and HS are statistically significant while OT and WT are not. Such results are consistent with previous findings of MANOVA over Y<sub>1</sub>–Y<sub>3</sub> (Table 4). Based on the within-subject effect, MANOVA identifies three significant interaction effects: WT × Year, WT × Season, and OT × Season. Similar to the previous MANOVA analysis (Table 4), this finding indicates that the effect of weather was not consistent, changing over times T<sub>1</sub>–T<sub>6</sub> and makes sense as weather contains uncertainty and varies over time. Unlike the previous MANOVA (Table 4), the statistically significant interaction effect of OT × Season ( $F = 6.03$ ,  $p = 0.02$ ) indicates that occupant behavior varies between heating-intensive and cooling-intensive seasons. This finding explains the assertion from profile analysis that Senior residents consumed more energy for heating and possibly less energy for cooling than Family occupants.

In summary, the MANOVA analysis revealed three important findings: (1) high performance buildings' energy performance remains consistent over multiple years; (2) construction type, technology level, and home size have significant impacts on energy use and such impacts are consistent over time; and (3) the two occupant types do not have a significant impact on energy use long-term while this lack of impact is inconsistent over shorter periods of time. Shapiro-Wilk tests were performed to test the model's normality. Results show that error terms of the MANOVA model are statistically normally distributed at a 95% confidence and suggest valid conditions of regression (Hill & Lewicki, 2006).

### 3.4. Economic impact analysis

Due to economic factors, it is assumed that low-income households use less energy; however, low-income does not imply low energy consumption. In fact, the energy use from low-income households has a considerable variation and it can be 26% higher than that from higher-income households (Berelson, 2014). A Tetra Tech (2012) report highlighted the fact that low-income residents often consumed more than higher-income residents because they were generally less aware of energy literature or in housing without EE systems and technologies. Therefore, this study used the average energy use of the Virginia population as the baseline to analyze economic impacts and financial

benefits.

According to the U.S. EIA (2016), residential electricity consumption in Virginia was 1117 kWh/month on average; the electricity price (per kWh) varied between \$0.1066 and \$0.1204 monthly and its average was \$0.1167/kWh. Based on HUD income limits, thresholds for low-income, very low-income, and extremely low-income families are 80% AMI, 50% AMI, and 30% AMI respectively. Virginia's AMIs from 2013 to 2016 were \$76,900, \$77,500, \$78,400, and \$77,500, respectively. The research team used these economic data as inputs in Eqs. (2) and (3) to calculate economic impact.

As a result, the financial benefit value (V) due to energy efficiency in LIHTC-assisted high-performance buildings equates to \$648 per year (i.e., \$54 per month). The financial benefit rates (R) equate to 9.3% for extremely low-income households, 5.6% for very low-income households, and 3.5% for low-income households. The average energy expenditures for low-income households with income thresholds of less than \$20,000, \$20,000–\$39,999, and \$40,000–\$59,999 were \$1719, \$1940, and \$2433, respectively. Therefore, the financial benefits due to energy efficiency as a product of LIHTC developments can reduce 26.6%–37.5% of energy cost for low-income households.

## 4. Discussion

### 4.1. Energy efficiency

This longitudinal study showed consistent energy performance across three years and confirmed the reliability of green-rated developments that have energy efficient systems and technology. Findings from data analysis strongly support the implementation of green building systems into future policies and finance mechanisms. Energy efficient housing is critical when considering overall energy demand and the cost of infrastructure and consumption, as the impacts are complex and far-reaching. In addition to environmental and economic implications, the fiscal health of a household can be closely tied to the cost burden of energy expenditure.

Prior literature and governmental reports have outlined the importance and impacts of energy efficiency in the residential housing sector (Dakwale, Ralegaonkar, & Mandavgane, 2011; Gillingham, Newell, & Palmer, 2009); however, energy-efficient houses are not necessarily easy to embrace. Historically, one of the primary barriers in the market is the developer's perception of higher initial costs associated with these homes and lower economic benefits (reportedly due to added personnel hours and use of innovative materials and technologies) (Konchar & Sanvido, 1998). In reality, residential units are constructed as inexpensively as permissible by market type to meet minimum requirements for current local codes and certification standards. This "low-bid" mentality is meant to keep first costs low, thus ensuring financial accessibility of clients and maximizing profitability for developers and homebuyers alike. In the past, little consideration was given toward energy efficiency and the additional expense of operation (primarily air conditioning cost) that result from building to minimum standards (Hayles & Dean, 2015; Ruparathna, Hewage, & Sadiq, 2016). Such practices have been found to be common when attempting to create housing accessible to low-income households. As a result, housing built to target a cost point with short-term financial motives and to minimum standards is often not as energy efficient as it could be. This lack of energy efficiency creates higher operating costs when compared to buildings where high-performance construction methods and materials are employed. The longer-term returns to developers who build and maintain high-performance building projects can be a remedy to this problem through improved maintenance costs and utility costs (Beheiry et al., 2006). This work provides concrete and durable evidence to support these decisions.

#### 4.2. Affordable housing

Data analysis indicates consistent cost savings in LIHTC multifamily green buildings. As previously mentioned, the economic impact owing to energy efficiency in green buildings is highly beneficial for low-income residents by reducing up to 25% of total household expenditure. Findings could have important economic and social implications that extend beyond energy efficiency to the development itself (Freedman & McGavock, 2015). Low-income housing developments affect the mix of residents within neighborhoods not only by increasing the availability of certain forms of affordable housing but also by potentially influencing the attractiveness of communities to different types of households and income levels. For example, LIHTC programs have provided funding for about one-third of all new units in multifamily housing built in the United States since the late 1980s (Khadduri et al., 2012). The housing investment under LIHTC has measurable effects on the distribution of income within and across communities and provides potential to leverage economic benefits through both affordable communities and energy savings.

Nevertheless, home energy expenditure posits a heavier weight in the low-income household's equation. Utility costs incurred from household operation hold the potential to create a financial hardship. The global trend of increasing energy consumption and cost will only further the financial burden placed on these households. While this is true for all households, irrespective of income level, it holds especially true in the case of low-income households. For these households, the cost of housing alone can constitute a significant portion of their gross income. Since it is widely accepted that housing cost should ideally not be more than 30% of one's gross income (Schwartz, 2014), this study illustrates how easily low-income households could spend more than 30% of their gross income on housing and associated operating costs. Additional hardships could also be realized as month-to-month and year-to-year energy costs are often not constant. As household energy demands fluctuate, dependent on climate conditions, so do monthly energy costs. This erratic monthly variance in the percentage of income allotted for housing is destabilizing to household finances. All households are affected by energy expenditure and rising energy costs could result in fewer households with the financial means to pay for increasing future energy expenditure. Economically, households with the lowest incomes are burdened the most by inflation. Therefore the ability, resulting from adopting energy efficient technologies, to save these operational costs contributes to stability in the household and the community.

#### 4.3. Energy retrofitting

Findings indicate that renovated buildings consistently demonstrate improved energy performance compared to new buildings. This improvement can be 12.5% and does not change over time. The authors speculate that this observation could be due to (1) the renovation projects in the sample do not have mechanical fresh air systems like the new construction projects in the sample; and (2) new construction units have more permanent light fixtures and wall outlets than the renovation projects, thus there is more opportunity for miscellaneous electric loads (MELs). Another possible explanation for the increased energy use in the new construction sample could be due to the Jevon's Paradox, used in environmental economics to suggest that the increased efficiency due to technological progress raises consumption (Polimeni, Mayumi, Giampietro, & Alcott, 2015). This paradox is difficult to measure empirically but makes sense for an interesting theoretical argument. Jevon's Paradox suggests occupants in a new housing unit might feel that they can use more energy because the unit is efficient, while those in a renovated unit might not see it as new. Other possibilities include the differences in technologies included in the unit or other variability unable to be studied in this work, a limitation, but the researchers are currently measuring a small subset of the sample using

circuit-level energy monitors. Results also suggest the necessity of energy auditing and retrofitting to update the existing stock since it is not always economically feasible to build new construction developments.

#### 4.4. Occupant behavior

The industry has an energy efficiency information gap – a lack of verified energy performance standards, real-time data, and post-occupancy feedback for residential projects. Human factors researchers have reported that people are generally poor at managing systems with lags in information and delayed feedback loops (Brehmer, 1992; Sterman, 1989). In the context of this research, the human-building socio-technical system is ripe for reducing the information gap and lag to occupants. Nahmens, Joukar, and Cantrell (2015) found that the top five behavioral factors that have a significant impact on the energy bills of low-income occupants are the following (in order of importance): (1) cooling setpoint during summer; (2) energy-saving practices/behaviors of households; (3) occupant behavior with respect to indoor environment quality; (4) occupant behavior with respect to lighting and electrical appliances; and (5) heating setpoint during winter. Zhao, McCoy, Du, Agee, and Lu (2017) identified four direct correlates between resident behavior and home energy use: temperature settings (winter/summer), use of a washer and dryer, and knowledge about building systems. Zhao et al. (2017) also identified two indirect correlates (increasing the effect) between technology and behavior: temperature settings specifically during winter and knowledge about building systems. This study suggests that occupant type does not have a significant impact on energy use while this lack of impact is inconsistent over time. Behavior remains critical to understanding the progress in energy efficiency and this variance highlights the potential.

Findings suggest that the senior occupants' seasonal energy use behavior present an opportunity for designers and engineers to improve building technologies that can accommodate senior occupants. Future investigations could focus on this subset of the population through purposeful design and construction to reduce this usage. Senior housing demand is increasing rapidly, as the U.S. 55+ population will reach 98.2 million by 2020 (Nyberg & Liu, 2009; U.S. Census Bureau, 2015; HUD, 2013) and the senior housing construction market is estimated to be between \$250–270 billion (CBRE, 2015; Worzala, Karofsky, & Davis, 2009).

### 5. Conclusion

This empirical study investigates time effects of energy efficient technologies and resident behaviors in green buildings for low-income residents from 310 residential units across many years (2013–2016). Results indicate high-performance buildings' stable and consistent energy efficiency across these years; units use more energy in heating seasons than cooling seasons; and results confirm that energy use fluctuates by season. Results also indicate similar energy use patterns for different construction types, while new units have significantly higher energy usage levels than renovated units. There are different energy use patterns based on occupant type as well, yet no statistically significant level difference ( $t = 1.66$ ,  $p = 0.24$ ) while senior residents used 9.9% more energy on average in heating than family residents (i.e., non-seniors). Senior occupants are not consistently using more energy than Family occupants over longer periods of time though. MANOVA analysis reveals three important findings: (1) high performance buildings' energy performance remains consistent over multiple years; (2) construction type, technology level, and home size have significant impacts on energy use and such impacts are consistent over time; and (3) occupant types do not have a significant impact on energy use over long periods of time while this lack of impact is inconsistent over short periods of time. The financial benefit value due to energy efficiency in LIHTC-assisted high-performance buildings equates to \$648 per year (i.e., \$54 per month). The financial benefit rates equate

to 9.3% for extremely low-income households, 5.6% for very low-income households, and 3.5% for low-income households. The financial benefits due to energy efficiency reduce energy expenditure by 26.6%–37.5% for low-income households.

This work contributes to the body of knowledge pertaining to human-environment interactions toward home energy efficiency since humans spend roughly 90% of their lives in buildings. First, these findings advance the understanding of human factors in the early design and construction phases, which reinforces current thinking of scientists and engineers to maximize the effect of technology investments. Second, these findings improve the understanding of the complex sociotechnical system for low-income groups, which represents the linkage of society, occupants, and the environment. These findings have implications for policymakers on the integration of green building policy into affordable and public housing systems. Results strongly suggest the success of governmental support in overcoming barriers, building public recognition of green buildings, and attracting industry-driven investments on green buildings.

It is important to recognize the limitations of this work. First, number of occupants was excluded in the model since the sample provided little variance and correlation. Second, energy use analysis focuses on electricity use only and energy costs in terms of \$/kWh. The analysis excludes utility taxes, tariffs, and services fees since the variability in utility fee and municipal tax structures across the state distort the energy use analysis. Third, although the findings are very likely to be applicable for other regions, they are not tested against differing geographic zones in this study.

This work provides an opportunity for future work. First, the samples in this study are green buildings certified by the EarthCraft rating, one of the only datasets currently available that allow for this type of inquiry. Other potential benefits of 3rd party rating systems may be analyzed. Another future study can explore tailor-made green technologies to specific occupants (e.g., senior resident) in ways that green buildings' energy saving potentials can be maximized. For future work, data collection can continue across a longer period of time and diverse geography, which may enhance findings of the time effects and climate.

## Declarations of interest

None.

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